Spray characteristics of air-assisted urea-SCR sprays of sub-atmospheric temperatures

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Abstract

Urea-based selective catalytic reduction (SCR) system is widely used to reduce NO_x emission from diesel engines. The NO_x conversion efficiency, as well as the adverse effects of wall-wetting is mainly influenced by the atomization characteristics of urea water solution (UWS). Under extreme winter conditions, the UWS can reach temperatures as close as its freezing temperatures. Under these adverse weather conditions the flow and spray characteristics of UWS are not well defined. In order to gain an understanding of these factors, an attempt has been made in this work to study the effect of varying the temperatures of UWS to evaluate the spray characteristics of UWS used in SCR systems. In this work, the temperatures of UWS were varied from 20°C to -10°C to consider the variations in the ambient temperatures from normal up to freezing point of UWS. Effect of temperature of UWS was significant at lower gauge pressures (ΔP) of the atomizing air. Bag breakup was observed at 20^{0}C and ΔP= 500 mbar condition in near-nozzle region of the spray. On the other hand, almost intact liquid core was observed at -10^{0}C and 500 mbar condition suggesting poor atomization of UWS spray. This observation was confirmed in drop-size distributions where large number of big droplets was observed at -10°C and low ΔP conditions. Drop-size distributions improved with increase in ΔP at all temperature conditions showing marginal influence of temperature of UWS at high ΔP conditions. This underlines the need of operating UWS systems at high ΔP conditions to mitigate the effect of sub-atmospheric temperatures UWS spray characteristics.

Keywords

UWS, spray characteristics, sub-atmospheric temperature, drop-size distribution

Introduction

Diesel engines are ubiquitous source of energy in many applications including heavy-duty applications, power generation as well as passenger and freight transport. Soot and NO_x are major harmful emissions from a diesel engine. Stringent emission regulations proposed for heavy duty diesel engines demand an efficient after-treatment system to control the NO_x and soot emissions. The injection of UWS in SCR systems is a commonly accepted strategy for NO_x abatement [1]. In this method, urea water solution (UWS, 32.5% urea by weight) is injected into exhaust manifold of an internal combustion engine. UWS undergoes hydrolysis and thermolysis processes to form ammonia vapour. Ammonia vapour then acts a reduction agent to decompose NO_x in the presence of a catalyst [2]. The conversion efficiency of the SCR system is mainly governed by atomization characteristics of UWS through mixing of UWS with exhaust gases of an engine. Moreover, non-vaporized droplets of UWS may impinge on a wall of the SCR system leading to urea residues. Thus, it is important to study spray characteristics of UWS spray [1, 2].

Spray characteristics of UWS are widely studied under non-evaporative and evaporative cross-flow conditions. Varna et al. [2] studied UWS sprays from a pressure-driven atomizer at 9 bar injection pressure at different velocities of cross-flow. Wall-hitting of UWS droplets was observed at low cross-flow velocities. Shi et al. [3] studied effect of injection angle of a pressure-driven atomizer on mixing length of a SCR system. They reported that orthogonal injection to exhaust flow leads to minimum mixing length. Spiteri et al. [4] compared air-assisted and pressure-driven atomizers. They reported that UWS sprays from pressure-driven atomizer are least affected by cross-flow velocities and lead to wall-impingement. On the other hand, air-assisted atomizers produce lower droplets Sauter Mean Diameter (SMD) resulting in better mixing of UWS and exhaust gases. Thus, air-assisted atomization strategy has gained attraction for atomization of UWS in SCR systems [4].

Most of the spray characterization studies have been performed on room temperature of UWS [1-3]. However, extreme winter conditions lead to freezing of UWS at -11^{0}C [5]. These extreme temperatures may affect spray characteristics of UWS. In order to gain an understanding of these factors, an attempt has been made in this work to study the effect of varying the temperatures of UWS to evaluate the spray characteristics of UWS used in SCR systems. In this work, the temperature of UWS was varied from 20°C to -10°C to consider the variations in the ambient temperatures from normal up to freezing point of UWS. High-speed shadowgraph method was used to evaluate the spray characteristics at different gauge pressures of the atomizing gas.

Experimental setup

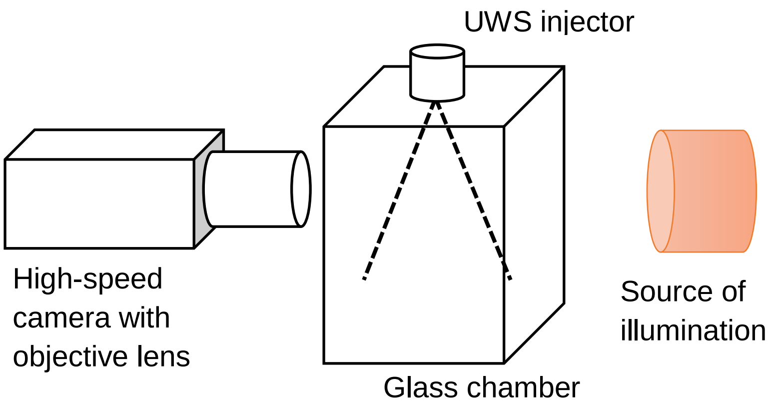

Fig 1. Schematic of experimental setup

The schematic of the experimental setup used in this work is shown in Fig. 1. High speed camera (Photron SA X-2) was used to capture shadowgraphs of UWS sprays at various locations. Near-nozzle spray structure images were captured in a window of 5.3 mm × 3.5 mm below the injector tip with 1,68,000 frames per second (fps). Global structure images of UWS sprays were captured using high-speed shadography method at 16000 fps with an exposure of 1 µs. Drop-size measurements were performed at 50 mm below in the injector tip with field of view of 20 mm × 3.5 mm. Shadowgraph images of droplets were then processed using a MATLAB image processing toolbox to calculate size of the droplets. Out-of-focus droplets and droplets with sphericity less than 0.8 were neglected for reliable drop-sizing [6, 7]. Statistically sufficient number of droplets (more than 4000 droplets) was ensured in drop-size distribution. Resolution of the imaging was 21.5 µm per pixel, thus, droplets with diameter less than 108 µm (5 times pixel resolution) were neglected.
Sub-atmospheric temperatures of UWS (20, 0^0C and -10^0C) were obtained using cooling bath of ice-salt solutions of various concentrations. Temperature of UWS was measured with K-type thermocouple within accuracy of $\pm0.5^0$C. Surface tension of UWS was measured using pendent-drop method (First Ten Angstroms, FTA100). The measurements were calibrated using deionized water as a standard liquid. Maximum mean standard error in the surface tension measurements was less than 1.1%. Surface tension values of UWS at various temperature conditions along with standard deviation and mean standard error are given in Table 1. It was observed that surface tension of UWS increased by 5% when its temperature dropped to -10^0C.
Air-assisted UWS injector of Albonair (liquid jet diameter=1 mm) was used in this work. The atomizer is externally-mixed and uses coaxial jet of air for breakup of liquid. The measurements were carried out at various gauge pressures of the atomizing air (500, 1000 and 1500 and 2000 mbar) conditions. Mass flow rate of UWS was kept constant at 1000 g /hr.

Table 1. Surface tension values of UWS at various temperature conditions

Temperature of UWS (^{0}C)	Mean surface tension (mN/m)	Standard deviation (mN/m)	Mean standard error (%)
20	73.69	1.18	0.53
0	73.75	1.07	0.51
-10	77.44	1.95	1.02

Results and discussion

Spray characteristics of air-assisted UWS sprays of sub-atmospheric temperatures were studied using high speed imaging method. The effect of sub-atmospheric temperatures of UWS on drop-size distribution, global and near-nozzle spray structures was studied at various gauge pressures of the atomizing air (ΔP).

Global spray structure images:

Global structure images showed the presence of liquid lumps and ligaments at low ΔP conditions suggesting poor atomization. Atomization of UWS improved with increase in ΔP showing finely atomized liquid at all temperature conditions.

Liquid temperature (^{0}C)

20^0	-10^0

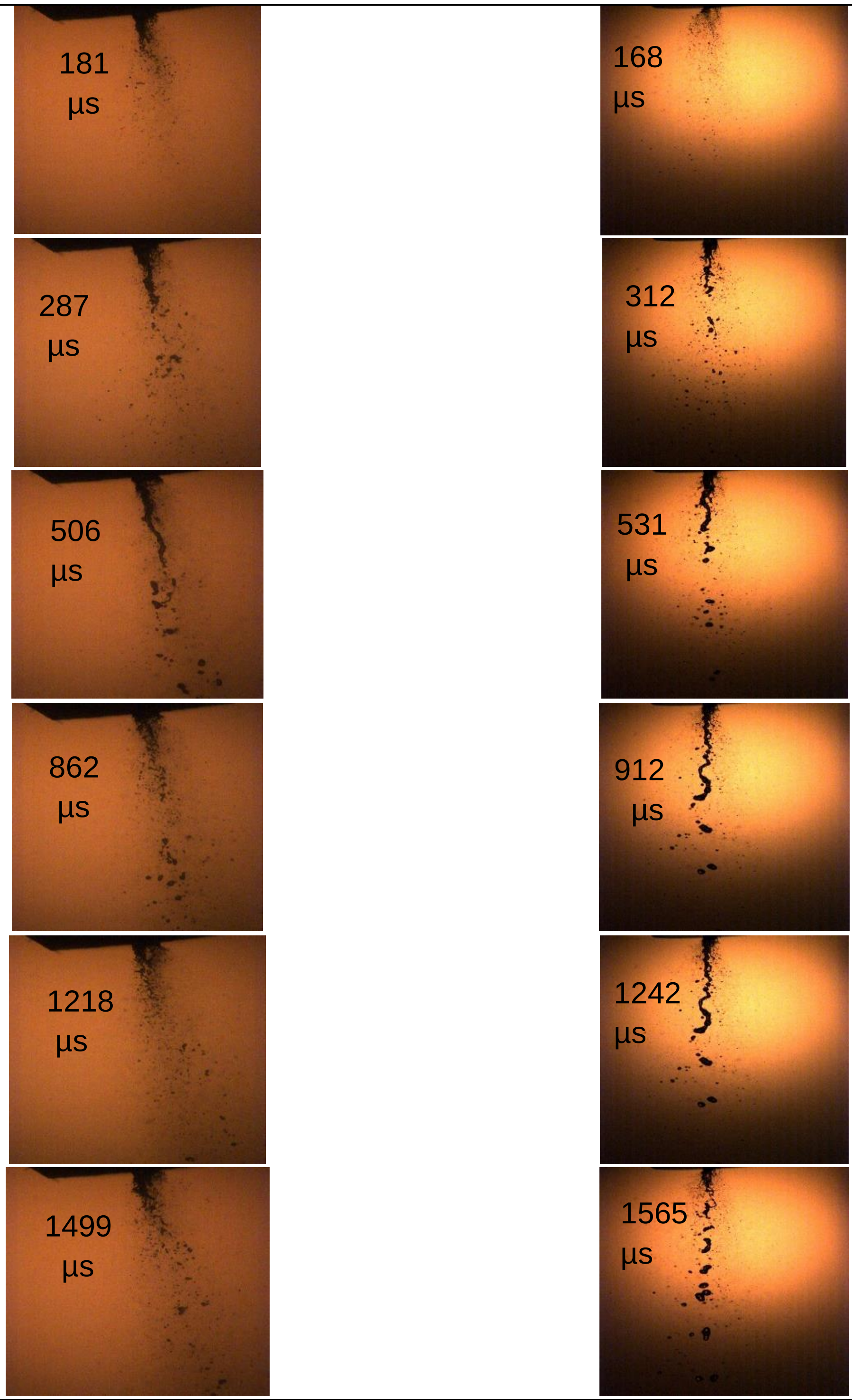

Fig. 2: Global structure images of UWS sprays of 20^{0}C and -10^{0}C for ΔP=500 mbar

Figure 2 compares instantaneous images of global structure of UWS sprays of 20^{0}C and -10^{0}C at ΔP=500 mbar condition. A large number of big droplets were observed at this ΔP condition due to poor atomization of UWS. At low liquid temperature (-10^{0}C), many liquid lumps and big droplets were observed as can be seen in Fig. 2. This could be because of poor atomization of UWS at -10^{0}C condition due to increased surface tension of UWS. Kinetic energy of the atomizing air at ΔP=500 mbar condition might not be sufficient to overcome surface tension force of the UWS. This could result in the formation of big droplets and liquid lumps at -10^{0}C condition. The presence of bigger droplets in the UWS sprays can be identified in drop-size distributions as discussed in next section.

Drop size distributions:

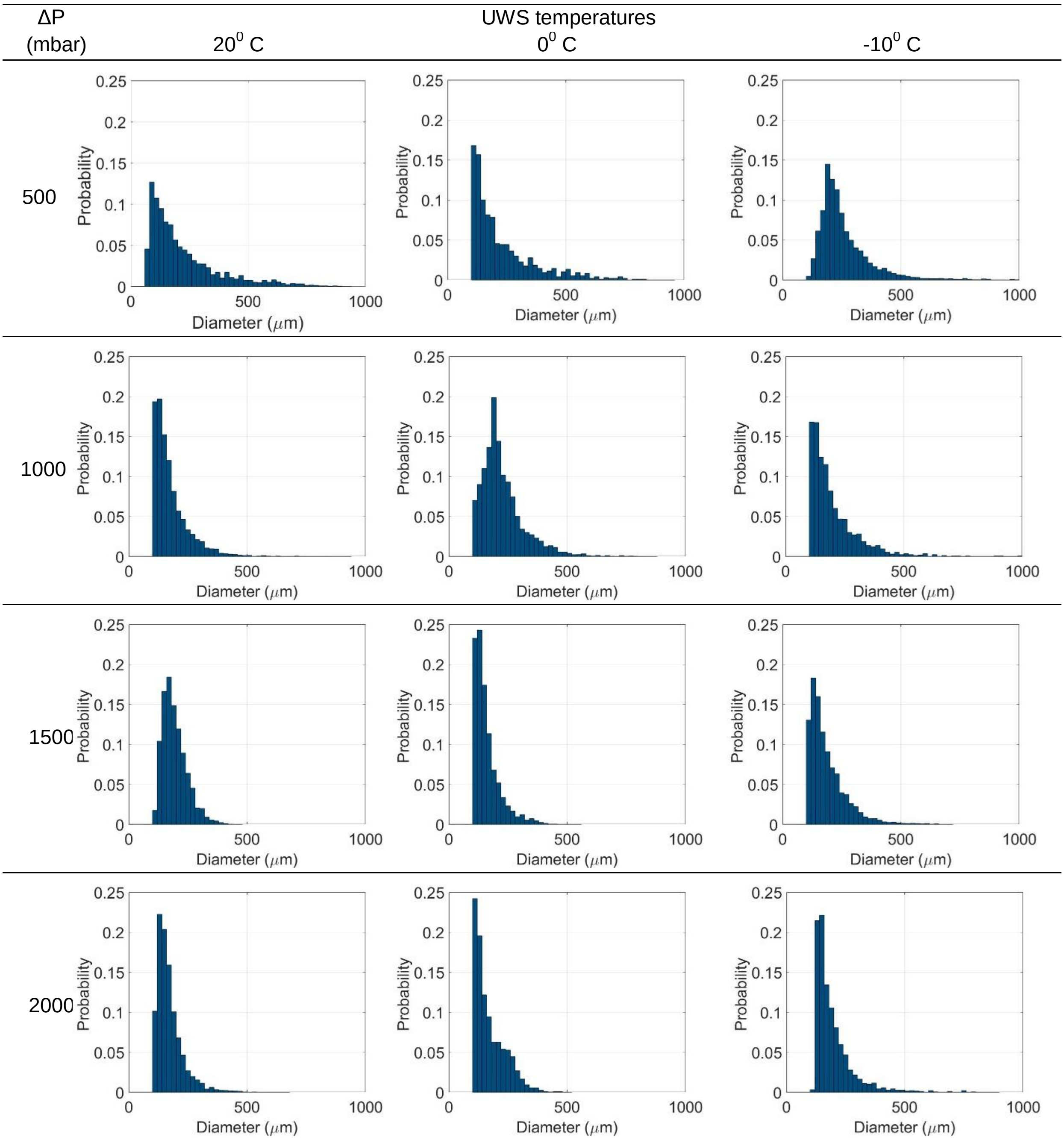

Fig. 3: Drop-size distributions of UWS sprays at various liquid temperatures and ΔP conditions

Drop-size distributions were studied for the three temperature conditions and for various gauge pressures of the atomizing air (ΔP) as shown in Fig. 3. It was observed that most of the droplets (more than 80%) were smaller than ~200 µm diameter at all operating conditions. Drop-size distributions became narrower with increase in ΔP due to better atomization of UWS. Maximum droplet diameter (D_{max}) reduced from ~750 µm to ~500 µm when ΔP was increased from 500 mbar to 2000 mbar at ambient temperature condition (20 ^{0}C). This can be attributed to secondary atomization of big droplets due to additional kinetic energy available in the atomizing air at higher ΔP conditions. High D_{max} value indicates presence of larger liquid mass that might lead to wall impingement due to high momentum and less evaporation of UWS. On the other hand, narrow drop-size distribution suggests presence of large number of small droplets those might evaporate quickly due to high surface area leading to better mixing of exhaust gases and UWS along with minimum wall impingement. Thus, ΔP has significant influence on drop-size distributions of UWS spray, and narrow drop-size distributions with D_{max} less than 500 µm can be obtained with high ΔP conditions (1500 and 2000 mbar).

UWS sprays of sub-atmospheric temperatures showed considerable variation in drop-size distributions at low ΔP conditions. Drop-size distributions were skewed towards right-side suggesting presence of large number of big droplets and high D_{max} values. D_{max} increased from ~750 µm to ~980 µm at ΔP=500 and 1000 mbar for -10 ^{0}C.

This could be mainly due to high surface tension of UWS at this temperature condition which resulted in poor atomization of UWS. This condition is undesirable as it might form urea residues on the walls along with significant reduction in NO_x conversion efficiency of SCR systems. When ΔP was increased, drop-size distributions of sub-atmospheric conditions showed narrower drop-size distributions. Further, D_{max} values at low temperature conditions were similar to those of room temperature condition. This suggests marginal influence of liquid temperature on drop size distributions at high ΔP conditions. This underlines the need of operating UWS systems on high ΔP conditions to mitigate the effect of sub-atmospheric temperatures UWS spray characteristics.

Near-nozzle spray structure:

Liquid temperature (^{0}C)

20^0 | -10^0

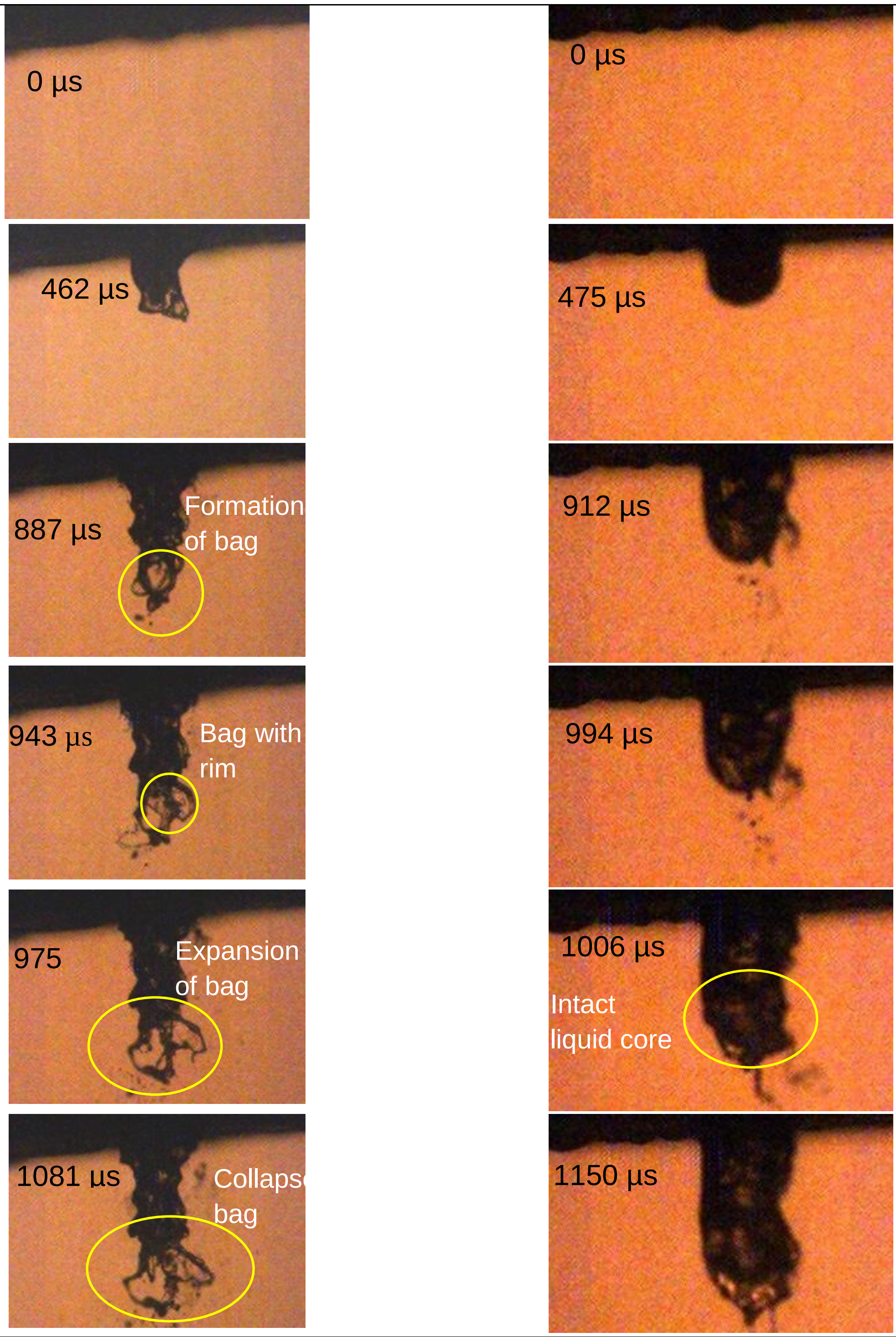

Fig. 4: Near-nozzle spray structure images of UWS sprays at two liquid temperatures and ΔP = 500 mbar condition

Near-nozzle spray structure images were captured to study the effect of liquid temperature on the process of primary atomization. The images were captured at 160000 fps with exposure of 0.29 µs. Figure 4 shows comparison of instantaneous images of near-nozzle spray structure at two temperatures (20 ^{0}C and -10 ^{0}C) for ΔP = 500 mbar condition. Bag breakup mechanism was observed at ambient temperature condition (20 ^{0}C) as can be seen in Fig. 4. The velocity and density gradients of the atomizing air and UWS triggers Kelvin-Helmholtz and Rayleigh Taylor instabilities causing formation of sheet along the surface of liquid lump. The sheet was further expanded by the atomizing air to form bag-like structure. This was due to competition between surface tension force of the liquid and aerodynamic force of the atomizing air. When the surface tension force was overcome by the aerodynamic force of the atomizing air, the bag was broken into droplets and ligaments as can be seen in Fig. 4 at 1081 µs. Relatively larger size liquid droplets and ligaments were formed from rim of the bag. Further, kinetic energy of the atomizing air at this gauge pressure will be low, which might result in relatively larger size droplets even after secondary atomization. This observation was confirmed in drop-size distributions of ΔP = 500 mbar condition where large number of bigger size droplets were observed.
UWS sprays under sub-atmospheric temperatures showed a difference in near-nozzle spray images, particularly at temperature of -10^{0}C. Almost intact liquid core was observed at this condition even at 1150 µs as can be seen in Fig. 4. This shows poor atomization of UWS at -10^{0}C and ΔP = 500 mbar condition. This might be due increased surface tension of UWS at -10^{0}C which opposes the liquid breakup. This might have resulted in more number of big droplets. This observation was also corroborated in the drop-size distributions as discussed in the previous section

Conclusions:

An experimental study was carried out to understand the effect of sub-atmospheric temperatures of UWS on spray characteristics. Global and near-nozzle spray structures and drop-size distributions of air-assisted UWS spray were studied at different gauge pressures of the atomizing air (ΔP). The temperature of UWS was varied from 20°C to -10°C to consider the variations in the ambient temperatures from normal up to freezing point of UWS. Drop-size distributions showed the presence of large number of big droplets at low ΔP conditions of 500 and 1000 mbar due to poor atomization of UWS. Drop-size distributions became narrower with increase in ΔP suggesting improved atomization. Near-nozzle images of UWS at 500 mbar and 20^{0}C condition showed bag breakup mechanism. On the other hand, almost intact liquid core was observed at -10^{0}C indicating poor atomization of UWS at this temperature. Also, drop-size distribution showed more number of big droplets with higher D_{max} due to high surface tension of UWS. This is undesirable, as more number of big droplets may reduce NO_x conversion efficiency and may lead to wall-wetting under extreme weather conditions at low ΔP. High ΔP conditions overcame the surface tension forces, and only marginal influence of sub-atmospheric temperature was observed on the UWS sprays. Thus, UWS systems should be operated at high ΔP conditions to mitigate the adverse effects of higher surface tension and sub-atmospheric temperatures on the atomization characteristics of UWS sprays.

Acknowledgements

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Nomenclature

UWS Urea-water solution (32.5% urea in water by weight)
SCR Selective catalytic reduction
ΔP Gauge pressure of the atomizing gas [mbar]
D_{max} maximum droplet diameter [µm]

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