Overspray Characteristics and Droplet Density Distribution of Low Pressure Shear Coaxial Injector

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Abstract

An HVLP (high-velocity-low-pressure) injector configured with a liquid-center and gas-outer nozzle can be extensively used in many industries, including automobile refinishing, wood furniture finishing and so on. The main problem of spray painting is overspray. Overspray produces much VOC (volatile organic compounds) which can cause bronchitis in an operator and waste paint or coating fluids. So, the aim of the present work is to reduce overspray and increase transfer efficiency. An HVLP injector with a gas post of 2-stages are designed and built to conduct spray characteristics as well as to increase transfer efficiency. This efficiency is critical to the spraying and coating from both a cost and an environmental regulatory standpoint. Droplet diameters are measured by laser diffraction methods considering the ratio of refractive indices inside and outside of the liquid sphere.

Experimental studies have been carried out to use the HVLP injector under various momentum ratios and Weber numbers. A higher momentum ratio and Weber number can achieve better atomization characteristics, but it can cause the super-pulsating phenomena which offers bad performance to painting process with film thickness. The experiment results show that the main effect of liquid jet break-up is governed with gas jets of the inner-stage. Additionally, gas jets of the outer-stage also contribute atomization at the far-field spray region and droplet transportation to the object. It was observed that, as gas jets increase, droplet mean diameters decreased and transfer efficiency increased due to the outer gas post which makes an air-curtain near the spray jets so that impinged droplet cannot overspray to the outer region of the spray jets.

Keywords: Overspray, HVLP, SMD, Impinging, Transfer efficiency

Introduction

Spray painting is used in many industries due to a wide working coverage which include rough and irregular substrates such as steel, metal decking and concrete products. It brings a great potential for cost savings in working time. Technologies in developed countries such as The United States, Europe, Russia and Japan have the core technology for many spray injectors applied to automobile repainting, wood finishing and pharmaceutical processing. Several factors affect painting quality and transfer efficiency. Spray paintings usually need to increase transfer efficiency which is defined as the ratio of mass or volume of solid coating deposition on a surface to the total mass or volume used in a painting application (ASTM D5009-89, EN 13966-1). Overall ranges of transfer efficiency with various spray guns are shown in Table 1. However, in the process of spraying, VOC and toxic PM (particle matter) are diffused due to the overspray. Overspray is the total amount of atomized droplets that do not stick to the object and is a defect of atomization characteristics. So, it can cause respiratory diseases in the operator. The most widely used of spray painting is airless spraying. Airless spray guns which are conventional pressure spray gun makes more overspray than HVLP (High-Velocity-Low-Pressure) spray guns due to the rebound and splashing characteristics of atomized droplets with high speed on the painting objects. Airless spray guns have a transfer efficiency typically in the range of 20~30% so that they can produce much VOC (volatile organic compounds). An HVLP spray system was developed to increase transfer efficiency and reduce overspray. The liquid jet break-up mechanism has been applied to a shear coaxial injector to apply paint with a high volume of dispersing air at low pressures. HVLP spray guns operated with a high volume of low velocity air stream that produces a larger mean diamter of droplets and reduces impact momentum of the atomized droplet. As shown in Figure 1, HVLP systems are configured with a spray gun and a 2-stage turbine blower. HVLP has many advantages that reduce overspray, VOC emissions, and HAP emissions. HVLP spray guns cannot use high solids with mid to high range viscosity. Fluid delivery rates with high viscosity liquids do not exceed 20 oz/min and lack the proper atomization required for some fine finishes [1].

Figure 1 HVLP spray system and spray image

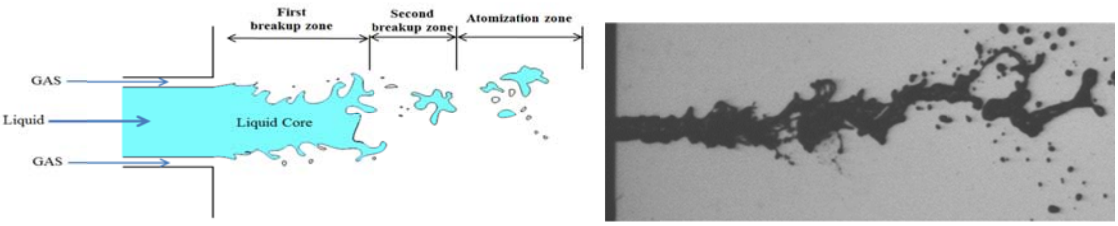


Figure 2 Schematic of liquid shear break-up with an air-blast injector

They are operated with an air cap pressure under 0.68 bar and an air volume flow rate over 840 l/min in compliance with the local regulations of EPA, SCAQMD, TNRCC and so on. The main benefits of the HVLP injector can improve transfer efficiency in the range of 60 to 80 percent more than airless spray gun.

In the case of the spray painting process, atomization characteristics with spray angle, volume flux distributions and droplet mean sizes are very important parameters. Also, transfer efficiency is governed by injector geometries and injection conditions with paint properties and air pressure. Therefore, as shown in Figure 2 the fundamental mechanisms of liquid jets break-up, droplets transport dynamics, droplet impact characteristics and atomization process must be investigated.

Gautam and Gupta[2] and Villermaux[3] showed that the momentum flux ratio is one of the main parameters for two-phase coaxial jet atomization and mixing. Also, the analysis on the spray structure of the coaxial jet was studied by Chigier and Beer [4]. They showed that the mean velocity ratio dominates the development of vertical structure and atomization. The main parameters of droplet behavior depend on the Weber number and surface conditions with a cold-dry surface, a wet surface or a hot surface. Impact characteristics are classified with pure rebound, rebound with break-up, splashing limiting and prompt splash.

So far, a limited number of spray painting and coating research related to theoretical and experimental investigations have been discussed and published in conferences and papers towards a better fundamental understanding of the atomization process. Flow visualization by an airless gun has been studied by Settles[5]. His results clearly showed that the key atomization process of painting with an airless and pressure atomizer occurs by the way of liquid sheet instability and breakup. Also, he explained spray entrainment, impingement and wall jet formation and asserts the needs for physics of sheet atomization of viscoelastic paints and attempt to match the actual paint sheet breakup characteristics. Overspray generation and fluid dynamics of spray painting are studied by Kwok and Liu[6] and Hicks and Senser[7]. Daws[8] investigated that Planar wall jet formed linear thickness with distance from the impinging point, and eventually to separate from the wall. Wen et al.[9] studied Stokes number which is related to the discrimination of the behavior of larger vs. small-particles. Domnick[10] showed that as droplets increase in diameter, transfer efficiency also increases and found that film surface depends on the effective viscosity of the impacting droplets. In previous studies of numerical analysis, Lindenthal[11] used PDA measurement, and numerical simulations of the coating process with the final aim of estimating the film thickness. Using the commercial Fluent^{Tm} program, spray behavior and film thickness distributions injected by a pneumatic atomizer was studied by Ye et al.[12] In the case of non-Newtonian fluids, the final spherical droplet is not produced due to the shear-dependent viscosity. Bai and Gosman[13] investigated that splashing clearly can happen under the circumstances of spray impaction and identified seven different wall impaction regimes. The main problem and issue of the spraying process is overspray characteristics. In order to understand overspray process related to transfer efficiency, it is necessary to analyze detailed investigations with droplet size distributions with various injection conditions and to understand the break-up mechanism, the impinging structure and overspray characteristics for the new 2-stage HVLP spray gun. Overall phenomenology of the 2-stage HVLP spray gun studied through flow visualization and optical measurement.

Experimental Procedure

The current study of overall spray characteristics was performed using the 2-stage HVLP spray gun. This system is configured with a multi stage blower and spray gun that outlet velocity of gas jet injected sonic conditions. The atomization process of the HVLP spray gun has the same mechanism as the shear coaxial injector that the main parameter of break-up is governed with shear force of a coaxial jet. The temperature of the ambient

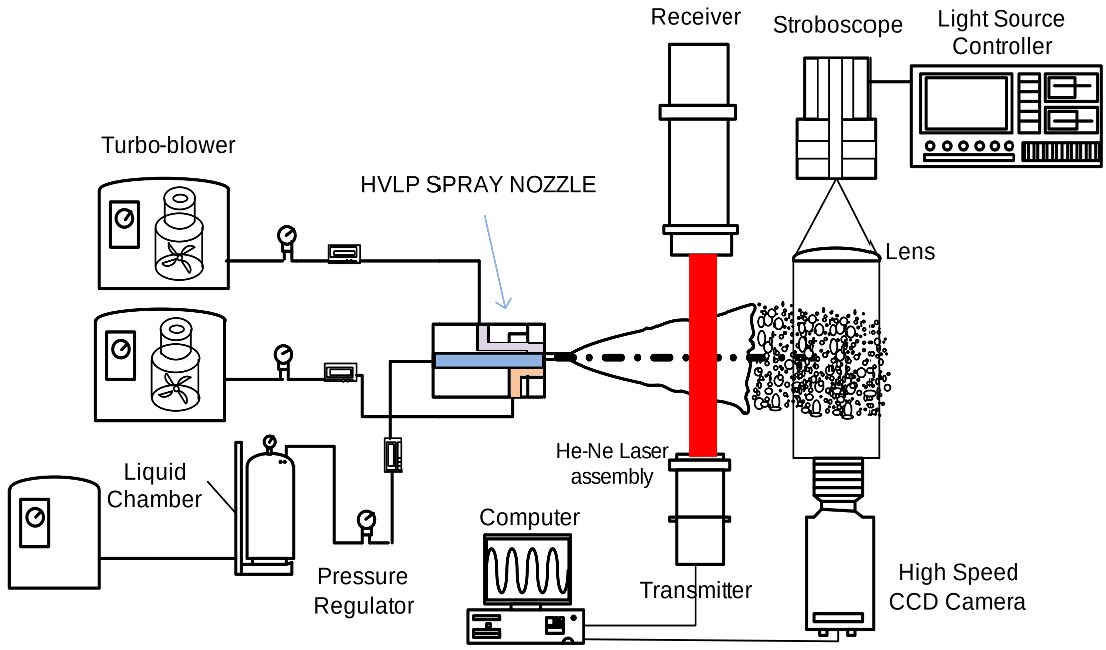


Figure 3 Schematics of HVLP spray system and measurement configurations.

Table 2 Specifications of HVLP spray nozzle and cross-section view

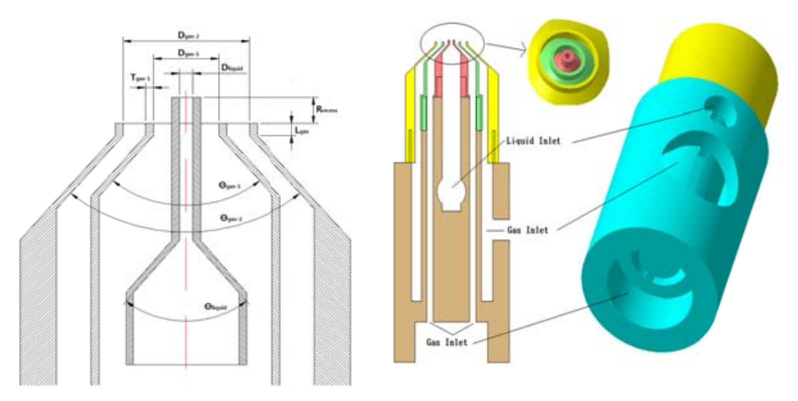
Specifications of HVLP spray nozzle		
D_{liquid}	1.07 mm	
D_{inner}	4.15 mm	
D_{outer}	8.00 mm	
T_{gas-1}	0.50 mm	
L_{gas}	0.84 mm	
R_{recess}	1.79 mm	
Θ_{liquid}	78°	
Θ_{gas-1}, Θ_{gas-2}	80°	

Table 3 Water & paint & ambient air properties

Parameter	Water	Transparent paint	Ambient air
Temperature (K)	293±2	290±2	295±5
Density (kg/m^3)	998	950	1.21±0.05
Surface tension(N/m)	0.0727	0.0391	-
Viscosity (cP)	0.9247	480.0	-

conditions was 290±3 K, the humidity was below 30% and the atmospheric pressure was 103.2±2.0 kPa. Figure 3 illustrates the schematic of the spray system. The HVLP spray gun is made of SM45C material and is processed with three different inlet passages with liquid, gas and gas inlet. A specification of the HVLP spray nozzle, the cross-sectional view and the HVLP nozzle assembly are shown in Table 2. 2-stage HVLP spray gun can inject gas from inner-stage and outer-stage. Water and Speed-Urethane of transparent paint was injected with various injection conditions. A summary of the specifications of water, Speed-Urethane, and ambient air is given in Table 3.Speed-Urethane shows the non-Newtonian characteristics with shear thinning and it can apply to various surfaces of steel, aluminum, FRP and ABS. Operating conditions with flow rate, velocity and non-dimensional number are shown in Table 4.

Table 4 Operating conditions of HVLP spray gun

Parameters	Range
Liquid flow rate (g/s)	2.1 ~ 12.17
Air flow rate (l/min)	93.0 ~ 98.4
Liquid velocity (m/s)	2.3 ~ 13.5
Air velocity (m/s)	144.0 ~ 151.3
Momentum ratio	5.0 ~ 110.5
Weber number of gas	372 ~ 410
Reynolds number of liquid	2243 ~ 14440

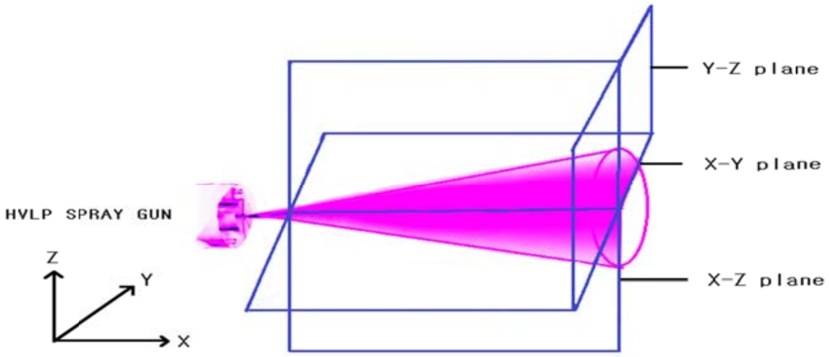


Figure 4 Coordinate configurations of spray cross-sectional view

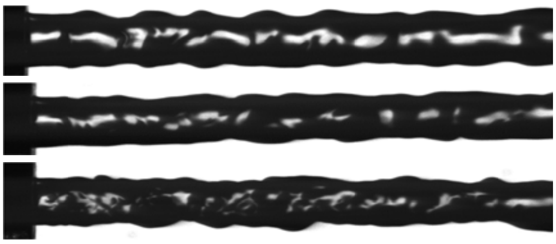


Figure 5 Liquid column deformation with various weber number. (L_{ori}/D_{ori} = 2.14)

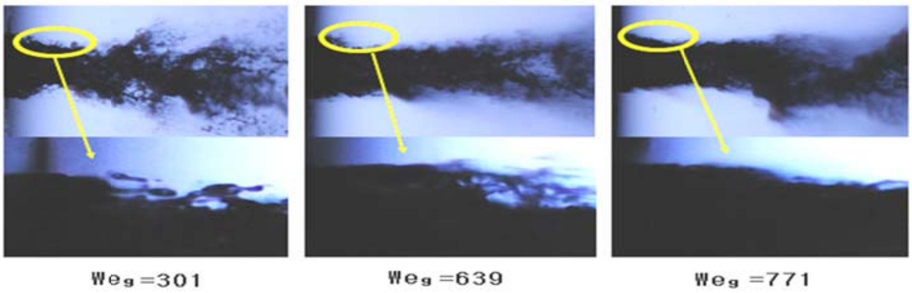


Figure 6 Shear break-up images with various weber number

For providing flow visualization and optical instrumentation to measure droplet sizes, the air curtain is installed in front of lens to prevent the contamination of droplets. Visualization of the break-up process with the spray structure was captured by a high speed CCD module. For each experiment, many images were captured and used to analyze the deformation of the liquid column and break-up of the spray jets. The cross-sectional view of the X-Z and X-Y coordinates are schematically illustrated in Figure 4 and captured with a laser sheet beam using a DSLR camera. Analysis of the spray images was averaged for each test condition in order to reduce any experimental uncertainty due to the unsteadiness of the spray structure. Test liquids were poured into a liquid tank and pressurized to 8 bars by an air compressor. A high volume of air was supplied by a 2-stage turbo blower. In the case of measuring mass flow rates with liquid jets, an accurate weighing machine is used with a resolution of 0.05 g. Volume flow rates with gas jets are measured by multiple nozzles in a chamber which is designed and noted by the standard methods with ANSI/AMCA 210-07, ANSI/ASHRAE 51-07 and KS B 0062.

The liquid mass flow rate was controlled by pressure regulators and measured by a turbine type flow meter which was calibrated to an uncertainty of less than 1.5%. Droplet mean diameters are measured by the laser diffraction apparatus with the Mie scattering technique considering the ratio of refractive indices of the liquid sphere. Depending on the optical properties of the droplets, scattered light may be absorbed and diffracted. The line-of-sight time-resolved droplet size measurements were conducted using a laser diffraction instrument that was manufactured by Sympatec (Helos/Vario-KF) with a 5 mW, 633 nm He-Ne laser with a 29 mm beam diameter. The receiver has 31 channel multi-element detector rings and 3 centering elements. The receiver was fitted with a lens with a focal length of 1000 mm with an R6 lens, so that droplet sizes ranged from 1.75 to 1750 μm. For a time resolved droplet size distribution measurement, the laser diffraction instrument was set to sample the diffracted light signal at the maximum acquiring rate of 2000 Hz. Spray shape with unbroken liquid core, regular ligaments, and un-uniform spherical droplets, where laser diffraction anemometry cannot be carried out reliably, were avoided for the determination of detailed spray jets. To investigate the transfer efficiency using the HVLP spray gun, a spraying booth, a high accuracy load cell, an oven, and a timer are used. The spray booth is configured with a test panel of 60cm x 60cm, air entrainment section and air outlet. Transfer efficiency determined by European Standard by CEN. EN 13966-1 which regulate "Determination of the Transfer Efficiency of Atomising and Spraying Equipment for Liquid Coating Materials – Part 1: Flat Panels" in method 2 was used for the evaluation.

Results and Discussion

-Spray image analysis-

Global spray structures are studied by a 2-stage HVLP nozzle. It is configured with three passages and liquid jets injected in the center of the nozzle. Generally, the atomization of the liquid jets is governed with internal geometry, viscosity, surface tension and the properties of the gaseous medium. Liquid jets are affected by the hydraulic and aerodynamic effect so that liquid jets experience the atomization process. Surface tension and aerodynamic forces are the main factors in the break-up of liquid jets. As shown in Figure 5, pure liquid jets injected into an ambient field show the deformation of a column wave. At the higher weber number of liquid jets, the hydrodynamic force with turbulent energy creates narrow surface waves. As the weber number increased, surface instabilities of the liquid column increased. Operating conditions of the HVLP spray gun is the liquid jet Weber number 261. However, the liquid column does not break-up in the condition of 261. So, we can know that the main parameter of break-up is the first gas jet injected at the first annular gap. To break the liquid column, gas must be injected by using the methods with shear forces. Figure 6 illustrates shear break-up images with various Weber numbers. The shear force of gas jets causes instability in liquid jets such as irregular ligaments of the liquid surface. The injection pressure of the air jets ranged from 0.2 bar to 1.0 bars. In the case of weber number 301 and Reynolds number 3000, fiber type break-up or superpulsating break-up showed. As the momentum ratio increased to 771, it is assumed that the liquid jets at the center post do not vibrate, but the liquid jet injected into an ambient file spins, and that rotating spray is formed downstream of the injector. Figure 7 shows liquid jet break-up images of the inner-stage gas injection and outer-stage gas injection. The inner-stage gas is injected with 0.23bar and a volume flow rate of 97.6 L/min. The outer-stage gas is injected with 0.13 bar and a volume flow rate of 218.3 L/min. The liquid is injected with 0.20 bar and a mass flow rate of 4.1 g/s. In a shear coaxial injector, shear forces around the liquid column is imposed on the liquid column to the droplets. So, as expected, the shear velocity has the most important influence on the column surface. Both inner-stage and outer-stage gas show the same atomization characteristics, however, in the case of outer-stage gas injection have longer break-up point of liquid column than inner-stage gas. For the outer-stage gas injection has less shear force to the liquid column than inner-stage gas injection. If operators use only the method of outer-stage gas injection, it would require a longer painting object due to droplet mean diameter which causes the surface quality.

However, air-curtain or air-barrier around the spray jets is mainly governed by outer-stage gas injection. Cross-sectional spray images of inner, outer and 2-stage gas injection are shown in Figure 8. With the various injection methods, impinging structure and overspray characteristics changed. Also, these results for the spray images show overall spray structures controlled with overspray. The inner gas injection shows more overspray characteristics than the outer gas injection and the 2-stage gas injection cases. Any droplets and mist are dropped down to the bottom region due to the gravitational force including both the inner gas injection and the outer gas injection cases. As expected, there is strong dependence on the outer gas injection to reduce overspray to the far field. It was observed that a significant effect of the air curtain by an outer gas injection prevents overspray and surrounds the spray jets. Droplet median and SMD (Sauter mean diameter) is used in painting and coating research and to evaluate the spray atomization characteristics. Also, the droplets transport and impinging process can be analyzed by median and SMD.

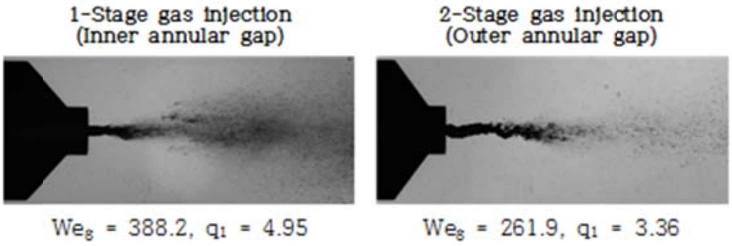


Figure 7 Liquid jet break-up images of inner-stage and outer-stage gas injection

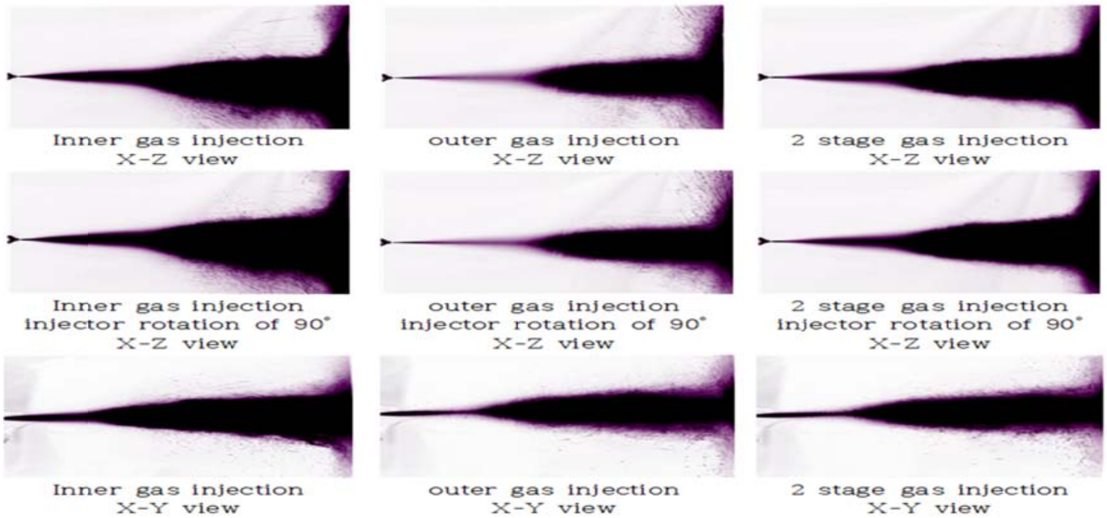


Figure 8 Cross-sectional spray images of inner-stage, outer-stage and 2-stage gas injection

Table 5 Droplet median and SMD of overspray water jet (220 mm)

Fluid	Parameter	Inner gas injection	Outer gas injection	2-stage gas injection
Water	Droplet median	60.18 μm	125.78 μm	46.13 μm
	SMD	45.49 μm	82.83 μm	30.87 μm
Transparent Paint	Droplet median	91.23 μm	151.24 μm	78.50 μm
	SMD	78.41 μm	107.58 μm	55.07 μm

Bi-modal distribution of SMD is illustrated to 362 and 373. Droplet size distributions of water and transparent paint are shown in Figure 9. The surface tension of water is 0.0727 and transparent paint is 0.0391. The viscosity of water is 0.924 cp and paint is 480 cp. In comparison with water and transparent paint, the droplet density distribution curve of transparent paint is extended to the large droplet region. Overall droplet sizes of paint are larger than water droplet. In Figure 10, the measured density distributions versus droplet diameters of inner, outer and 2-stage gas injection are compared. Droplet size distributions are very similar with inner gas injection and outer gas injection. The atomized droplets by an inner gas injection and outer gas injection are not uniformly distributed at 500mm. Outer gas injection produces more large droplets with a median of 148.47 μm than inner gas injection due to the aerodynamic force which is related to the injection velocity of gas and the effective contact point of the liquid column. Two peaks of density distributions changed to a one peak curve with normal distribution. The 2-stage HVLP spray gun produces small droplet median more than inner gas injection due to that fact that outer gas injection breakup droplets after the primary atomization process with inner gas injection. According to these curves, the 2-stage HVLP spray gun shows more high film quality than inner and outer gas injection. Table 5 shows the droplet median and SMD values of the overspray jet with various gas injection methods. When comparing overspray jet or not, overspray jets of inner and outer gas injection show less droplet median and an SMD of about 20~30 μm. In case of 2-stage gas injection, droplet median and SMD shows just about 3~5 μm. These results indicate that droplet sizes are just related with overall size distributions of the spray jet. However, the density distributions of overspray show 30 times less than spray jet. The 2-stage HVLP spray gun has the good mechanism with atomization and surrounding the atomized droplets to the painting surface.

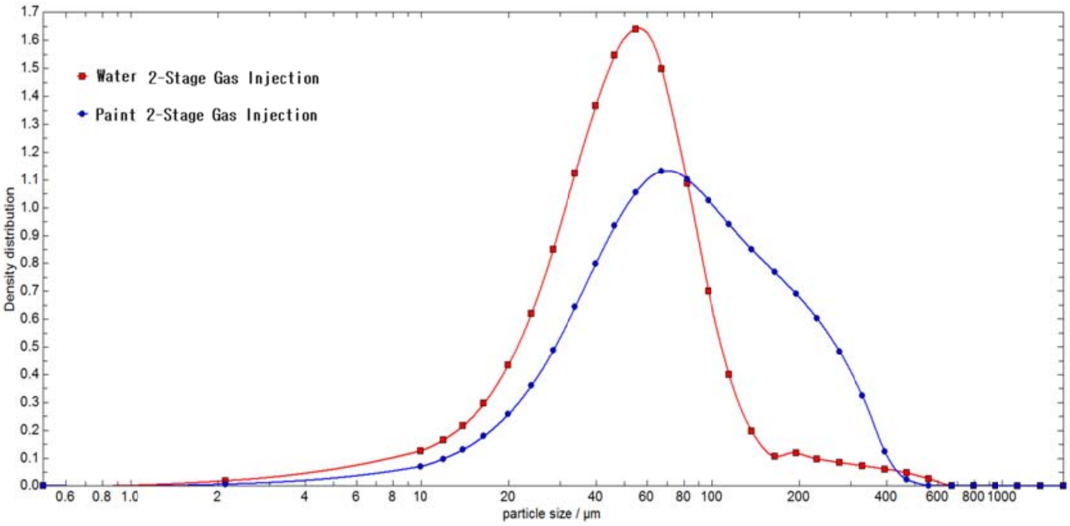


Figure 9 Droplet size distributions of water and transparent paint. (500 mm)

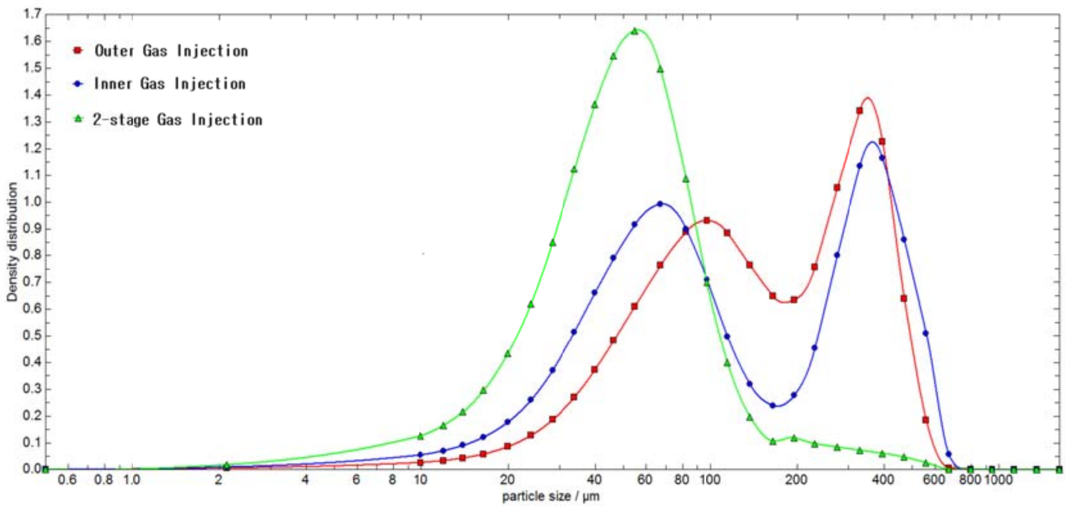


Figure 10 Droplet size and density distributions of with various injection methods. (500 mm)

Table 6 Summary of Transfer efficiency with various gas injection methods

Product	**2-stage HVLP spray gun**		
Spray gun prototype			
Gas injection methods	**Inner gas injection**	**Outer gas injection**	**2-stage gas injection**
Transfer Efficiency (%)	**65.2**	**62.3**	**71.2**

$$\mathbf{T.E} = \frac{\mathbf{100\ \times\ \mathit{Mass\ of\ coating\ solids\ deposited\ on\ target}}}{\mathbf{\mathit{Volume\ of\ fluid\ delivered}\ \times\ \mathit{density\ of\ coating\ fluid}\ \times\ \mathit{wt\%\ solids\ of\ coating\ fluid}}}$$

A summary of the measured transfer efficiency is given in Table 5.Transfer efficiency is expressed as the percentage of the weight by the painting target. This efficiency is critical to the painting from an environmental regulatory standpoint. Impacting and influencing factors of transfer efficiency are substrate characteristics, operator variability, spray methods, air conditions in the spray booth and liquid properties. Test standards of transfer efficiency are listed in EN 13966-1 (Determination of the Transfer Efficiency of Atomising and Spraying Equipment for Liquid Coating Materials - Part 1: Flat Panels). The mass in transparent urethane paint are loaded by a high precision load cell. Then, a spray gun located next to the aluminum foil within 300 mm and spraying time is maintained for 5 seconds. The percentage value of transfer efficiency is averaged over three times for each condition. As a result of these experiments, 2-stage gas injection using the 2-stage HVLP spray gun have a good transfer efficiency due to the effect of outer gas which encircle the spray jet to the painting surface. In case of the outer gas injection, transfer efficiency shows the lowest value of 62.3 % due to the large droplet distributions and no effect of an air curtain.

Summary and Conclusions

This experiment is to demonstrate the overspray characteristics through a comparison of gas injection methods. The 2-stage HVLP spray gun by flow visualization and laser diffraction method shows the break-up process and droplet size distributions. The main factor to break-up liquid jets is air velocity which can facilitate the break-up of liquid jets. A higher momentum ratio can achieve better atomization characteristics. Inner gas injection near the liquid nozzle gives more shear force to atomization than outer gas injection. Inner gas injection has more overspray characteristics than outer gas injection and 2-stage gas injection. Atomized droplets are dropped down to the bottom region due to the gravitational force. As expected, there is a strong dependence of outer gas injection to reduce overspray to the far field. Using the 2-stage HVLP spray gun, transfer efficiency is measured by the standard method with EN-13966-1. Measured transfer efficiency achieved 71.2% in a wet condition. As expected, the transfer efficiency increases with the effect of the air-curtain.

Acknowledgements

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