Paint Atomization and Paint Film Formation

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The special surface appearance of complex surfaces restricts the coating film quality of spraying. The study of the atomization and film formation characteristics of typical complex surfaces, as well as the spraying mechanism, is essential for planning the spraying robotic trajectory and improving the spraying efficiency. Modeling and characteristics of the atomization and film formation process, based on CFD numerical simulations in previous studies, are systematically reviewed, focusing especially on airless spraying. In addition, the advantages and disadvantages of the existing research from the perspective of numerical models and methods are discussed. Finally, a further research direction for spraying on complex surface is prospected. Overall, a comprehensive and up-to-date review of spray atomization and film formation characteristics is considered valuable to practitioners and researchers in these fields, and will facilitate the further application of robotic spraying in the mechanical, automotive, marine, aerospace, petrochemical and other industries.

numerical simulation computational fluid dynamics airless spraying complex surfaces robotic spraying

1. Introduction

Within industrial production, surface coatings have certainly asserted themselves as a key field, especially in oil and gas pipeline construction [1][2], automotive manufacturing [3][4] and equipment anticorrosion [5][6][7], with the overarching goal of enhancing protection performance while meeting the functional requirements in practice. Compared to brushing and rolling, coatings obtained by spraying are widely used, owing to their superior coating quality, higher efficiency and adaptability.

The spraying methods include air spraying [8][9][10], electrostatic spraying [11][12], plasma spraying [13][14][15], high-pressure airless spraying [16][17], etc. Airless spraying, owing to its unique spraying principle, always features excellent film quality, spraying efficiency, coating adhesion and environmental friendliness, and it is capable of achieving high-viscosity, high solid component and thick-coat spraying. Moreover, there is no air-assisted in atomization process, thereby avoiding film defects caused by impurities in the compressed air. The airless spraying process is essentially a gas–liquid two-phase turbulence flow movement of paint droplets in the air phase, which can be divided into the paint atomization process and the film formation process according to the time sequence, as is schematically shown in **Figure 1**.

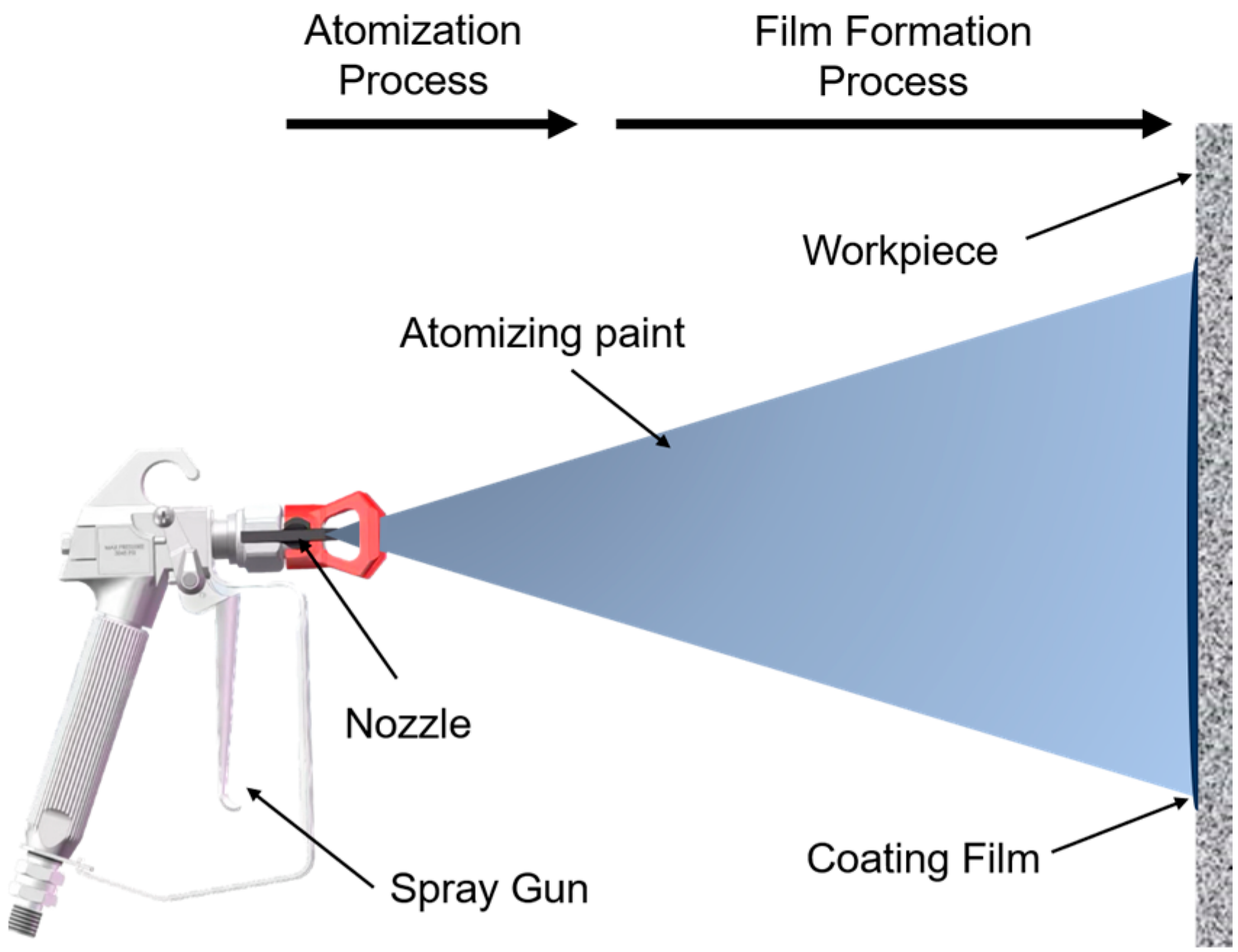

Figure 1. Spraying process with an airless spray gun.

Nowadays, robotic airless spraying is increasingly replacing manual spraying in coating applications. However, a major problem encountered in robotic spraying is the poor film quality on complex surfaces, namely orange-peel-like surfaces, sagging, graininess and locally uneven surfaces frequently occur. Consequently, it results in film thickness calculation, coating thickness control and trajectory planning challenges for robotic painting.

Essentially speaking, the reason is, first of all, the lack of understanding of the characteristics and mechanisms of the atomization of the spray. Adequate atomization results in smaller and more homogeneous paint droplets, leading to better film uniformity. Secondly, there remains a gap in in-depth research on the characteristics and mechanisms of film formation on complex surfaces, leading to an inability to set the optimal spraying parameters for each kind of surface. For instance, when spraying on a plane, the spraying gun can always be perpendicular to the surface of the workpiece, uniformly moving in a straight line, and ensuring the uniformity and stability of the coating film. Due to the influence of workpiece geometry, the vertical distance from the nozzle to the workpiece, the incident angle of paint droplets relative to the workpiece, and the movement speed of the spraying gun all accordingly change during dynamic spraying, which results in increased difficulty in offline programming of the robotic arm movement. Additionally, complex surfaces seriously impact the diffusion of the paint flow field. Owing to the phenomenon of boundary layer separation, it will produce localized vortex areas and reflux, resulting in localized splashing and excessive deposition when the paint moves to the near-wall zone, thus affecting the uniformity of the film thickness and the transfer efficiency (TE).

2. Historical Overview of Paint Atomization Properties and Mechanisms

2.1. Mechanism Study of Atomization in Airless Spraying

In order to comprehensively analyze research progress in the field of spraying, it is necessary to first overview the theoretical development from a historical perspective. The theory of high-pressure airless spray atomization essentially originates from the liquid jet atomization theory, which refers to the physical process in which a liquid becomes a large number of discrete liquid drops with different morphologies by dispersing and crushing the initial continuous liquid column ejected from the nozzle into the gas environment due to the role of extrinsic energy. During the dispersing and breaking up process, the paint will be subjected to the combined interaction of various forces such as viscous force, inertial force, aerodynamic force and surface tension. In the theoretical investigation of the causes of atomization, the theories of pressure oscillation [18], aerodynamic disturbance [19], turbulence disturbance [20][21], air disturbance [22] and changes in boundary conditions [23] are mainly formed.

Among them, the aerodynamic interference theory is the most fully developed hypothesis, and recognized by most researchers on account of it being a better explanation of the cause of atomization of low-speed liquid jets. Consequently, researchers generalized it and took it as the basic theory for high-speed jet atomization research. According to this theory (also called the liquid surface wave instability breaking mechanism, or linear instability theory), after the paint liquid is sprayed out of the nozzle, unstable waves will be produced between the gas–liquid interface under the influence of itself and the ambient atmosphere; in other words, surface waves in a certain wavelength range are unstable. With the temporal and spatial development, the surface amplitude increases eventually, leading to a breakup of the jet flow.

In the study of jet atomization forms, the main categories are divided into circular jets [24][25][26] and liquid film jets, according to the spray pattern resulting from the shape of the nozzle. The most common jet film shape in airless spraying belongs to the fan-shaped liquid film in liquid film jets. Therefore, a historical overview of the theoretical study of liquid film jets is mainly outlined here.

Liquid film jets are formed when a high-pressure liquid is instantaneously ejected through a slit. After the ejection of the liquid, the amplitude of the surface vibration wave of the liquid film generated by the airflow disturbance increases to a certain extent, such that the top of the jet loses its stability and breaks up into liquid lines, forming the initial atomization. As the liquid continues to move forward in time and space, the size of the initially atomized liquid line exceeds the critical size value for maintaining the steady state, generating secondary atomization and further breakup into microdroplets until the next steady state is reached.

According to the different shapes, they can be roughly classified into planar liquid films, fan-shaped liquid films and annular liquid films, as shown in **Figure 2**. York et al. [27] investigated the breakage mechanism of planar liquid films, pointing out that liquid film breakage is affected by the wavelength and frequency of the liquid film surface wave, the surface tension and viscosity of the liquid film, the flow rate of ambient atmosphere, the density of the gas or liquid, etc., and concluded that the increase in the amplitude of the surface wave is an important reason for the breakage of the liquid film.

Figure 2. Type of liquid film jet: (**a**) planar liquid film [28], (**b**) fan-shaped liquid film [29], and (**c**) annular liquid film.

In the early research of fan-shaped liquid film jet atomization, Squire [30] proposed the liquid film stability theory. Subsequently, Hagerty et al. [31] further investigated the stability of liquid films, indicating the symmetric and asymmetric waves of the liquid film, and concluded that the asymmetric waves were responsible for the fragmentation of the liquid film. Fraser et al. [32] found that fragments of liquid are broken off the wavy sheet, which then suffers continuous disintegration by air action, tending to contract into unstable ligaments, and that the mode of disintegration is critically dependent upon the ambient density. The size of droplets broken by surface wave shows variability, and the size distribution of droplets broken by liquid film perforation displays homogeneousness, while the direction of the droplet movement broken by edge stripping remains stable. What is in agreement between Dombrowski [33] and Fraser is that they considered the perforation of the liquid film to be the main reason for the formation of liquid ligaments, and concluded that the higher the surface tension and viscosity, the more difficult the liquid film is to break up, and that the density of the liquid has little effect on the disintegration. The higher the surface tension and viscosity, the more difficult it is to break the film, and the density of the liquid has little effect on breakage. Cao et al. [34][35] utilized the linear instability theory to explain the atomization of a viscous liquid when it is injected into a compressible gas atmosphere.

The aforementioned reports on the dispersion and atomization of jets are given in order to solve the problem of jet stability. Accordingly, starting from the basic control equations and boundary conditions of the jet on this basis, the dispersion relation for the development of small perturbations in the free liquid surface can be inferred using the

Normal Model Method, and through theoretical and numerical analyses, explanations of the mechanism and mechanical causes of the jet crushing and atomization are derived. Nevertheless, none of these theories can explain the cause of jet production satisfactorily and independently, and the theories even contradict each other. Despite the underdevelopment of the liquid surface wave instability breakup mechanism, it is the most accepted atomization theory and the mainstream research direction for current jet atomization. Furthermore, coatings are characterized by a variety of features, such as viscosity, volatility and complexity of composition compared to simple liquid jets, which affect the atomization characteristics, and the physicochemical properties of paints also must be taken into account in future atomization studies.

2.2. Experimental Study of Atomization in Airless Spraying

In earlier studies, atomized flow field data was measured by an MgO method [36][37]; however, the measurement results are poor and only a small amount of particle size data of spray can be obtained at a time. Teng et al. [38] investigated the airless spraying atomization characteristics at various pressures using the MgO indentation method. In order to obtain more spray information without affecting the atomized flow field, a series of optical measurement techniques, such as Digital Holographic Microscopy [39], Particle Image Velocimetry [40] and Planar Laser-induced Fluorescence [41], have been applied to the field of atomization research. Subsequently, the droplet concentration in the region of the flow field far from the nozzle, the velocity of the paint droplets and the size of the spray particles generated by the rotary atomizer were successfully obtained [42][43][44][45]. However, owing to the limitations of optical measurements and the complexity of the near-nozzle region, it was still difficult to dive into the near-nozzle region atomization process in a high-speed spray flow field represented by airless spraying. Based on experimentally measured spraying parameters, a series of mathematical models describing the size and velocity of atomized droplets utilizing Stochastic Resonance (SR) matrices similarly allow for simple analysis of the spraying parameters with respect to the atomization effect [46][47][48][49]. However, matching of the surface tension, coating viscosity, etc., with the SR matrixes is not considered, and is not of universality. By setting up a high-speed digital camera visualization system, Naz et al. [50][51][52] visualized and compared the airless, full-cone and hollow-cone jet patterns produced by nozzles with different outlet diameters, and obtained data on the jet dynamics and vortex clouds formation process during atomization of liquids at high temperatures and pressures.

3. Historical Overview of Paint Film Formation Properties and Mechanisms

3.1. Mechanism Study of Paint Film Formation in Airless Spraying

As a subsequent step to the atomization process, the film formation mechanism of sprays has also evolved. Paint film formation can be categorized as spray transfer and droplet deposition. The atomized paint undergoes spatial transfer in the flow field, where the impact with the workpiece and paint deposition occurs at the near-wall surface. Some small droplets drift away from the wall with the flow of the air phase. The spray transfer process can be essentially described as a turbulent flow in which the momentum and mass are transferred to each other in gas–liquid phases. The modes of paint droplet impact on the surface of the workpiece are summarized into the adhesion mode, rebound mode, spread mode and splash mode [53], which are related to the velocity and incidence angles of the droplets, as well as the roughness, temperature and surface moisture of the workpiece. The four impact modes of the droplets are shown in **Figure 3**. Additionally, the large pressure gradient of the droplets at the wall results in the boundary layer flow. Inside the boundary layer, the fluid immediately adjacent to the wall is completely adhered to the object surface, which is a viscous flow. When outside the boundary layer, the velocity gradient is very small, the viscous force can be ignored, and the flow can be regarded as a non-viscous or ideal flow. In the case of a high Reynolds number flow, the Navier–Stokes equations can be simplified to the boundary layer equations, owing to the rather thin boundary layer, based on the order of magnitude comparisons of scales and rates of change in velocity. In terms of film formation evenness, there is one more factor worth noting: the more a paint wets a surface, the more the amplitude of evenness is increased.

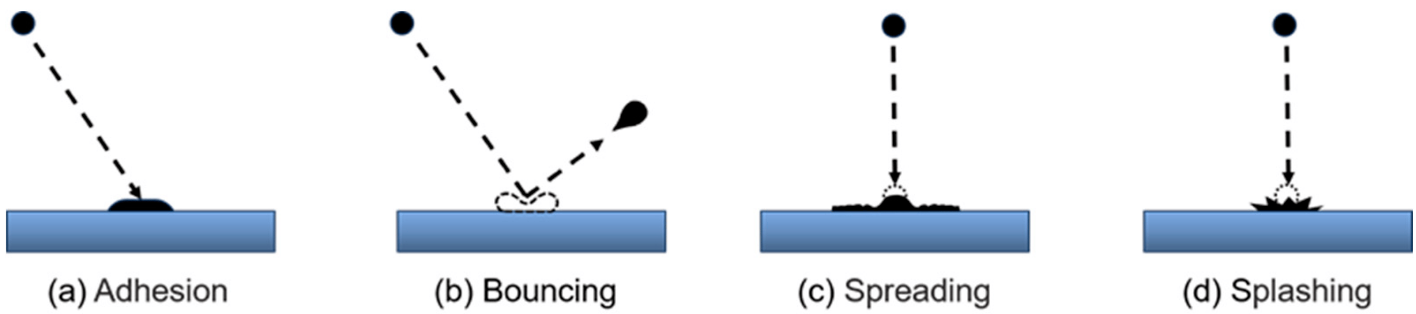

Figure 3. Impact modes of the paint droplets.

McCarthy [54] and Mirko [55], respectively, found that paint droplets with low surface tension and high viscosity impacting a wall hardly rebounded or splashed and, in some special cases, it can be simply assumed that deposition occurs whenever a paint droplet impacts the target surface, and the thickness of the coating film is only related to the velocity of the near-wall droplets perpendicular to the wall. Santon [56] and O'Rourke [57] proposed a wall-film model that can better predict the process of liquid film formation when a droplet impacts the wall.

3.2. Experimental Study of Paint Film Formation in Airless Spraying

Domnick et al. [58], for the first time, utilized a Phase Doppler Anemometer (PDA) to measure the velocity and droplet diameter during spraying, and explored the effects of these factors on the film thickness distribution by varying the air flow rate, spraying distance, and coating velocity. Similarly, Ye et al. [59] used a PDA and a Spraytec particle sizer based on laser diffraction to measure and calculate the spray velocity distribution by changing the initial and boundary conditions, thereby obtaining the localized coating film thickness on the workpiece surface. Xu [60] carried out an experimental study on the relationship between the spray pressure and the spray mass flow rate of an airless spray gun, and improved the coating film quality by gun trajectory optimization. Plesniak et al. [61] first summarized the TE of airless spraying with the correlation as a function of the actual spray momentum rate (SMR) and Sauter mean diameter (SMD), and Teng et al. [62] likewise reported the main influencing factors and the law of the paint transfer efficiency of airless spray using the electronic weighing method. Chen et al. [63] investigated the relationship between the TE and the curvature of the sprayed surface, and performed trajectory planning for the spraying gun. The TE of more paint spray technology was reviewed by Poozesh et al. [64] a few years ago.

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