Crop Protection 112 (2018) 201–208

Contents lists available at ScienceDirect

Crop Protection

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

Establishment of a static nozzle atomization model for forest barrier treatment

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ARTICLE INFO

Keywords:
Atomization model
Droplet size
Spray axis velocity
Computational fluid dynamic simulation method
Forest barrier treatment

ABSTRACT

Currently, the theory of using automatic target spray technology for forest barrier treatment in China has some shortcomings. Therefore, this study established an atomization model for two common brands of nozzles (Lechler and Feizhuo) used in this field. This model includes the two most important parameters: droplet size and spray axis velocity. A specific model for the two brands of nozzle was obtained. The obtained droplet size calculation model was validated with actual tools, which showed that at six different pressures, the average absolute error of the theoretical data for the droplet size obtained from the selected Lechler nozzles was 6.92 μm compared with the actual measured data, whereas the average relative error was 3.07%. The absolute and average relative errors for the Feizhuo nozzles were 11.41 μm and 4.43%, respectively. The model had a high degree of confidence. The test also verified that the droplet sizes at different distances from the same nozzle did not vary dramatically at a given pressure in the close-up range (30–50 cm). In addition, the droplet sizes at different angles did not significantly vary at given pressures and flow rates. However, droplet sizes that had the same angle increased as the flow increased. The classical theoretical model of spray axis velocity in connection to this study also improved, and the test results were verified by the computational fluid dynamic simulation method. Compared with the simulation data, the average absolute error of the improved theoretical data for the Lechler nozzle was 0.64 m/s for the selected nozzles, and the average relative error was 6.42%. The absolute and average relative errors for the Feizhuo nozzle were 0.67 m/s and 6.00%, respectively.

1. Introduction

At present, the prevention and control of forest pests is an important challenge of China's forestry program. In recent years, the annual average area of occurrence of the common pine caterpillar and the poplar leaf pests alone was more than 2 million hectares. Control treatments were applied to an area of approximately 1.6 million hectares, but the level of control only reached 68–70%, which caused a huge economic loss (State Forestry Bureau, 2016). For all the common pests, some of the larvae climb to the crown along the trunk of a tree at night or on weak sunny days to eat buds and new branches (Wright et al., 2010). In response to this problem, Kang and co-authors developed an automatic targeted application system using a barrier treatment based on laser detection technology. The system targetted pests by spraying pesticides on the trunk, which is the only route for larvae cutworms climbing to the crown. More than 90% less pesticide was applied with this method compared with a traditional broadcast spraying application, which significantly reduced the cost of leaf pest control and environmental pollution (Kang et al., 2012).

A shortcoming of this automatic target spray system was the liquid being applied only to the curved surface at the bottom of the trunk, but the spray drift, the droplet rebound from the trunk, and the loss from the trunk surface have not been studied in depth. The initial atomization was formed at the outlet of the nozzle after the liquid was sprayed from the nozzle. Then the liquid was ejected into the air and finally reached the surface of the trunk. In this process, the initial atomization of the liquid largely determined the latter liquid's spray behavior (Kang et al., 2014). Therefore, to solve the problem regarding this liquid's spray behavior, it is necessary to establish an atomization model of a nozzle for forest barrier treatment. At present, studies on nozzle atomization models for industrial use mainly have concentrated on the fields of engines, water jet cutting, and high-pressure cleaning, and most of the research is into high-speed jets in high-pressure environments. In all of these studies, the internal structure mechanism of the

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https://doi.org/10.1016/j.cropro.2018.06.001
Received 22 December 2017; Received in revised form 5 June 2018; Accepted 6 June 2018

nozzle was the research focus. For example, Goney studied the effect of cavitation and backpressure on the internal flow and spray of a real diesel engine nozzle with a specific air density (Goney, 1999). Mulemane and co-authors compared different numerical simulation models (a single-phase model and a two-phase flow model that took the bubble dynamics into account) of the cavitation flow in a diesel engine nozzle. Using a numerical simulation comparison of the two models for different types of diesel engine nozzles, some of the existing phenomena that could be observed from the test were confirmed (Mulemane et al., 2004). In addition, Barker and Selberg studied the effect of the nozzle size on the cutting performance of the water jet nozzle by changing the length of the transition section of the nozzle and the size of the inlet cone angle, and obtained the optimal length-diameter ratio of the transition section (Barker and Selberg, 1978). With a numerical analysis of the single-phase and multi-phase flows for the internal flow field of the water jet, Liu and co-authors showed that the axial velocity of the jet was faster in the initial stage and that the abrasive velocity at the outlet cross section had a "hat-type" distribution. The velocity attenuation and distribution of the different abrasives were similar within the nozzle (Liu et al., 2004). In agriculture, the studies of nozzle atomization models mainly have focused on field operation, anti-drift for a canopy, and an increased amount of liquid deposition. Most spray angles are large, and the research object has the characteristic of a large surface area. For example, Ferguson and co-authors noted through wind tunnel experiments that the nozzle type and choice of spray parameters (spraying pressure, wind speed, etc.) could reduce the liquid drift and improve canopy permeability (Ferguson et al., 2016a, 2016b). Duga and co-authors reported that the outlet pressure of the nozzle and the tree structure would have an effect on the overall liquid deposition rate, through analysis of three typical sprayers (Duga et al., 2015). However, the nozzle atomization model for the forest barrier treatment showed a large difference, which was characterized by a narrow spray angle with an environment of low pressure and low spray velocity. This finding was attributed to the fact that the target of the nozzle was the trunk surface and the spray area was small. Models for the atomization of such a narrow spray angle nozzle under low pressure and low spraying velocity are rare at present.

The focus of this study was to establish a nozzle atomization model for forest barrier treatment that is different from other industrial and agricultural nozzle atomization models. The main relevant parameters to be analyzed in the model included the droplet size and the spray axis velocity at different distances from the nozzle outlet, and all parameters were measured in a low-pressure environment (0.1–0.35 MPa). Based on the basic theory of jet flow, we improved the theoretical models of predecessors and obtained a specific theoretical model for the forest barrier treatment, and the relationships among nozzle pressure, nozzle shape, and the two parameters mentioned earlier were preliminarily determined. Finally, we validated these theories using practical experiments and simulation methods.

2. Materials and methods

2.1. Selection of nozzle types

In this study, the requirement was to form a barrier treatment width of 10 cm or more when the distance from the trunk was 40 cm and to have a liquid amount sufficient for preventing the migration of pests. The current agricultural nozzle manufacturers are mainly concentrated in Teejet (America) and Agrotop (Germany). Selecting these two nozzle manufacturers because they produce flat fans for row crops (boom sprayers) and hollow cones for bush and tree crops, and the commonly used angles are relatively large. If, however, the liquid's target is the trunk, a large spraying angle is not desirable; thus, we adopted industrial nozzles whose spray angles were smaller. Industrial nozzles are used for a variety of reasons, and they occupy a large share of the narrow-angle nozzle market. In this study, we adopted the two mainstream brands of nozzle in the international market and the Chinese market, and these nozzles were the Lechler nozzle, made in Germany, and the Feizhuo nozzle, made in China. These two brands of nozzles have broad applications in surface treatment, the food industry, mechanical processing, environmental protection, agricultural plant protection, and many other areas. Among different nozzle types of these two brands of nozzles, solid cone nozzles, hollow cone nozzles, and fan-shaped nozzles are the main types used in plant protection. Solid cone nozzles mostly are used for cooling, disinfecting, and dust proofing; hollow cone nozzles mainly are used for gardens, bushes, and tree crops. To spray the forest barrier band for this study, it was necessary to form a certain width of liquid on a specific ring-shaped area of the trunk. Selecting the cone-shaped nozzle would lead to uneven spraying, environment pollution, and other flaws. Because the spray section of the cone nozzle is round, the liquid amount cannot be better controlled at the edge of the trunk. The spray section of the flat fan nozzle is a narrow ellipse, however, so the plane is perpendicular to the ground when the nozzle is installed. When the spray platform is moving, this configuration can better ensure that the liquid is effectively sprayed on the trunk without waste. Using a flat fan nozzle can more easily achieve the desired spray result by controlling the spray time. Therefore, we selected a fan-shaped Lechler 632 series nozzle in this study, along with the Feizhuo H/U series nozzle. Then different angles and flow types were selected to meet the needs of the experiment. The nozzles selected in this study are given in Table 1.

2.2. Theoretical basis

The experiment in this study served the field of tree trunk spray application, which mainly focused on the value of the volume in the study of particle size. Therefore, we measured the droplet sizes with the volume median diameter (VMD), which generally is used for volume control and liquid flow (Mugele and Evans, 1951). The expression is as follows:

$$D_v = \left(\frac{\int_{D\,\min}^{D\,\max} D^3 dN}{\int_{D\,\min}^{D\,\max} dN} \right)^{1/3} \tag{1}$$

where D_v is the VMD of the atomized droplets, in m; D is the droplet diameter, in m; and N is the number of droplets whose diameter values are D.

2.2.1. Theory of positive correlation between the diameter of atomized droplets and the fan-shaped liquid film for fixed nozzles

In this study, the liquid film sprayed from the nozzles was fan shaped. While it was sprayed from the nozzle, the liquid film's late development was affected mainly by flow characteristics, gas or liquid physical properties, and flow conditions. The liquid film was disturbed by the outside gas and formed a vibration wave on its surface. The amplitude of the vibration wave increased so that the liquid film was finally broken up into fine droplets. For a given fan-shaped nozzle, the VMD of the atomized droplets from the fan-shaped liquid film was related to the nozzle spray pressure and the flow rate of the liquid according to the following formula (Dombrowski and Fraser, 1954; Dombrowski and Johns, 1963):

$$D_v \propto \left(\frac{q_m \sigma_l}{\rho_g^{1/2} \Delta P^{3/2}} \right)^{1/3} \tag{2}$$

where q_m is the mass flow rate of the liquid film, in m^3/s; ΔP is the difference between the spray pressure and the ambient gas's back pressure, in MPa; σ_l is the surface tension coefficient of the liquid, in N/m; and ρ_g is the density of the ambient gas, in kg/m^3.

The following formula can be obtained from formula (2):