果 树 学 报 2017,34(9):1161-1169
Journal of Fruit Science

DOI:10.13925/j.cnki.gsxb.20170031

气力雾化风送式果园静电弥雾机的研制与试验

王志强[1,2],郝志强[1,2],刘凤之[1,2],王孝娣[1,2],张敬国[3,4],王海波[1,2*]

([1]中国农业科学院果树研究所,辽宁兴城 125100;[2]农业部园艺作物种质资源利用重点实验室,辽宁兴城 125100;[3]潍坊市高密中等专科学校,山东高密 261501;[4]山东省高密市益丰机械有限公司,山东高密 261501)

摘 要:【目的】解决我国葡萄产区植保作业劳动强度大、作业质量差、雾滴易飘移等问题。【方法】应用机械设计理论与方法,根据葡萄树体结构不同,采用分段、独立式喷雾结构设计方案,研制了一种与四轮拖拉机或履带拖拉机配套的、适于葡萄园作业的气力雾化风送式果园静电弥雾机。该机动力由拖拉机的后动力输出轴经万向传动轴输送到机具后方,带动空气压缩机、柱塞泵和风机工作。测试并分析了不同压力下的喷头喷雾量、开启和关闭风机时的雾滴尺寸,并对棚架、V型架和篱架栽培模式下的葡萄树进行了样机田间试验。【结果】当开启风机时,雾滴体积中径(VMD)为72 μm,雾滴数量中径(NMD)为60 μm,雾滴扩散比(DR)为0.83;而关闭风机时,VMD为110 μm,NMD为80 μm,DR为0.73。田间试验开启静电系统时,棚架、V型架和篱架3种栽培模式下葡萄树外层叶片正、反面的雾滴平均附着率分别为35.4%、89.4%,92.0%、44.0%和86.1%、34.4%,内层叶片正、反面的雾滴平均附着率分别为27.5%、71.0%,86.1%、34.4%和72.7%、31.1%;关闭静电系统时,棚架、V型架、篱架3种栽培模式下外层叶片正、反面的雾滴平均附着率分别为30.8%、76.9%,82.0%、40.0%和82.9%、36.8%,内层叶片正、反面的雾滴平均附着率分别为25.0%、65.4%,80.6%、32.1%和67.7%、29.6%。开启静电系统使棚架、V型架和篱架葡萄树外层叶片正、反面和内层叶片正、反面雾滴平均附着率分别提高了14.9%、16.3%、10.0%、8.6%,12.2%、10.0%、6.8%、7.3%和9.4%、12.5%、7.4%、5.1%。【结论】气力雾化、风送和静电相结合的弥雾技术增强了雾化效果,提高了雾滴的均匀性和吸附性,有效防止了雾滴的飘移。

关键词:果园;气力雾化;风送喷雾;静电喷雾;弥雾机

中图分类号:S66 文献标志码:A 文章编号:1009-9980(2017)09-1161-09

Design and experiment of an air-atomized, air-assisted and electrostatic orchard sprayer

WANG Zhiqiang[1,2], HAO Zhiqiang[1,2], LIU Fengzhi[1,2], WANG Xiaodi[1,2], ZHANG Jingguo[3,4], WANG Haibo[1,2*]

([1]Research Institute of Pomology, Chinese Academy of Agricultural Sciences, Xingcheng 125100, Liaoning, China; [2]Key Laboratory of Horticulture Crops Germplasm Resources Utilization, Ministry of Agriculture, Xingcheng 125100, Liaoning, China; [3]Weifang Gaomi Secondary Specialized School, Gaomi 261501, Shandong, China; [4]Shandong Province Gaomi City Yifeng Machinery Co., Ltd., Gaomi 261501, Shandong, China)

Abstract:【Objective】For solving the problems of large labor intensity, poor work quality and pesticide drift of plant protection in grape production areas of our country, improving the orchard mechanization level and combining with the research status of anti-drift spray technology by domestic and foreign scientists.【Methods】The mechanical design theory and methods were applied and an air-atomized, air-assisted and electrostatic vineyard sprayer was developed in view of the characteristics of standardization vineyard in China, and the vineyard sprayer took the four-wheel tractors and crawler tractors as power and it was connected to tractors by the traction mechanism. The power was transferred to the rear components by the rear power output shaft and the universal joint shaft and the rear components such as the compressor, piston pump and fan were started. The main parts of the compressor, piston pump and fan and other compo-

收稿日期:2017-02-12 接受日期:2017-04-09

基金项目:中国农业科学院科技创新工程(CAAS-ASTIP-2015-RIP-04);国家现代农业产业技术体系建设专项(nycytx-30-zp);农业部"948"重点项目(2011-G28)

作者简介:王志强,男,助理研究员,硕士,主要从事果园机械的研发与推广工作。Tel:15184292566,E-mail:wangyewangzhiqiang@126.com

*通信作者 Author for correspondence. Tel:13591963796,E-mail:haibo8316@163.com

nents were fixed on the frame by the steady. The vineyard sprayer was made up of the air-atomized system, the air-assisted system and the electrostatic system. The compressor and the atomization nozzles were the core components of the air-atomized system. The compressor was selected in the light of the spray volume of the nozzles. The atomization nozzles were designed in accordance with the principle of air atomization. The air-assisted system was composed of the fan and the fan was chosen by the air flow and pressure. The number and size of the air outlets were determined by the different cultivation patterns of grapes. The electrostatic system was composed of the electrostatic generators and electromagnetic valves and its power was supplied by the battery of tractors. The charging way of the electrostatic system was contact charging and the high-voltage electrodes were connected directly to the atomization nozzles. The electrostatic generators were chosen because of the advantages which was that low-voltage power was required and the high-voltage static electricity was generated. According to the different structures of the grape trees, the vineyard sprayer could also spray partially and independently by controlling the different spray switches and could prevent the waste and pollution of pesticides. The spray capacity of nozzles was tested in the conditions of the different pressures. The droplets sizes were also tested when the air-assisted system was started and closed. The droplets sizes included the volume median diameter (VMD) of droplets and the number middle diameter (NMD) of droplets. The diffusion ratio (DR) was calculated by the VMD and the NMD. According to the NY/T 992—2006 "air-assisted orchard sprayer operating quality", the field experiment was carried out in the conditions of trellis, espalier and V form cultivation and a work speed of 1.5 $m \cdot s^{-1}$.【Results】The 9-195A type centrifugal fan was chosen, and the number of the air outlets was determined to be 13 and the size of the air outlets was determined to be 20 mm×80 mm. The HX7.5 type compressor and the BSD50-1218 type electrostatic generators were selected, and the atomization nozzles of the patent number "2012 2 0330431.0" were designed and authorized. The VMD of the droplets was 110 μm, the NMD of the droplets was 80 μm and the DR was 0.73 when air-assisted system was closed. The VMD of the droplets was 72 μm, the NMD of the droplets was 60 μm and the DR of the droplets was 0.83 when the air-assisted system was started. The VMD and NMD of droplets were reduced with the help of the air-assisted system and the DR had an increase of 13.7%. The average adhesion rates of droplets in leaves on positive and negative sides outside the trees reached respectively 35.4% and 89.4% , 92.0% and 44.0%, 86.1% and 34.4%, and the average adhesion rates of droplets in leaves on positive and negative sides inside the trees reached respectively 27.5% and 71.0%, 86.1% and 34.4%, 72.7% and 31.1%, when the electrostatic system was opened in the conditions of trellis, espalier and V form cultivation. The average adhesion rates of droplets in leaves on positive and negative sides outside the trees reached respectively 30.8% and 76.9%, 82.0% and 40.0%, 82.9% and 36.8%, and the average adhesion rates of droplets in leaves on positive and negative sides inside the trees reached respectively 25.0% and 65.4%, 80.6% and 32.1%, 67.7% and 29.6% when the electrostatic system was turned off in the conditions of the trellis, espalier and V form cultivation. The average adhesion rates of droplets were increased respectively 14.9%, 16.3%, 10.0%, 8.6% and 12.2%,10.0%, 6.8%, 7.3% and 9.4%, 12.5%, 7.4%, 5.1%. The electrostatic system increased the adhesion rates of droplets.【Conclusion】The combined technology of three spray technologies which included the air-atomized spray, air-assisted spray and electrostatic spray was used by the orchard sprayer and the orchard sprayer had the good atomization effect, reduced the sizes of droplets, enhanced the penetration of droplets, and improved the adsorption capacity of droplets.

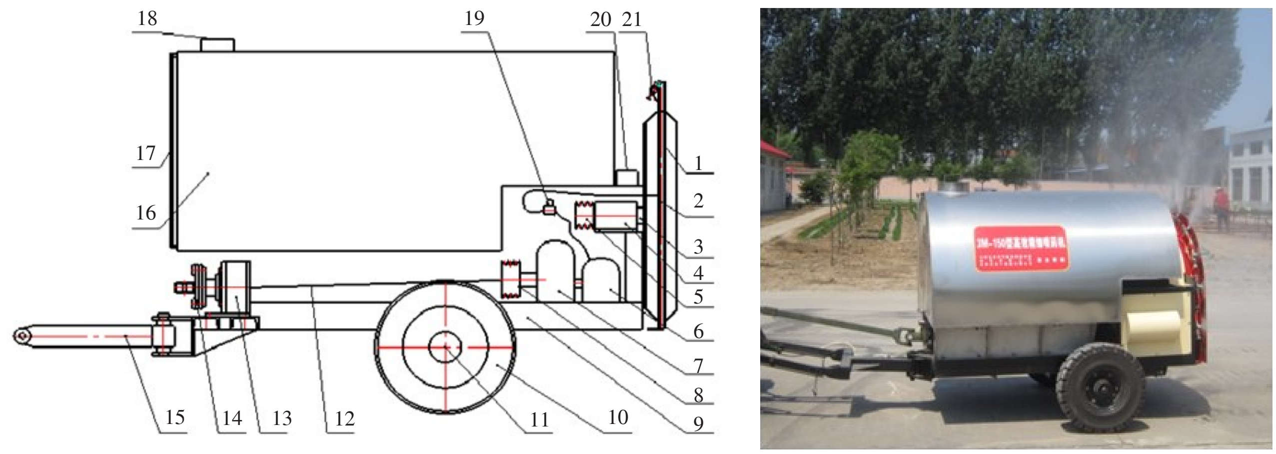
Key words: Orchard; Air-atomized; Air-assisted spray; Electrostatic spray; Sprayer

植保作业是葡萄生产中的重要环节之一，其质量直接影响葡萄的经济效益。目前，我国的果园机械化总体仍处于起步阶段[1]，很难满足果树产业现代化发展的迫切需求[2]，大部分葡萄产区仍然以人力植保作业为主[3]，不仅劳动强度大、作业质量差、而且雾滴易飘移，而雾滴飘移是造成农药危害的主要途径之一[4-6]。在发达国家，针对农药的流失和飘失问题，主要采用气流辅助式防飘喷雾、罩盖式循环喷雾、自动对靶喷雾和静电喷雾等技术，其中以气流辅助式防飘喷雾技术最为成熟[7-9]。Delele等[10]研究了果园风送喷雾机气流速度衰减、汇聚和穿透等特性，总结出气流衰减、扩散规律，为风送喷雾机风机设计提供了理论支撑。Endalew等[11-12]建立了风送果园喷雾机气流场CFD（computational fluid dynamics）模型，并进行了模型验证的田间试验，为喷雾机作业参数优化提供了基础模型。我国科研工作者也对气流辅助式防飘喷雾技术和静电喷雾技术做了相关研究，王军锋等[13]建立了风幕式静电喷杆喷雾试验台进行雾滴飘移试验，研究表明风速与静电能够减少雾滴飘移，而该试验荷电装置的电极采用环形针状组合电极，所需充电电压需上万伏，绝缘性能要求较高。张玲等[14]对双风道风送静电喷雾系统进行了试验研究，结果表明测试距离喷头0.2 m处的雾流荷质比可达1.08 mC·kg^{-1}，雾流有效射程超过4 m，水敏纸0.5~4.0 m均可获得理想的正反面雾滴沉积。贾卫东等[15]对常规喷杆喷雾扇形喷头设计了一种双平板感应式荷电装置，并搭建风幕式静电喷杆喷雾系统。试验结果表明，风幕作用能够改善雾滴在各冠层的沉积分布均匀性，静电作用能够改善雾滴在冠层中的沉积分布均匀性以及沉积效果。

笔者针对我国标准化葡萄园的特点，研制了一种气力雾化风送式果园静电弥雾机并进行了样机的田间试验。根据葡萄树体结构的不同，设计了分段、独立式喷雾，测试和分析了不同压力下的喷头喷雾量、开启和关闭离心风机下的雾滴尺寸以及开启和关闭静电系统下的雾滴附着率。

1　整机结构与工作原理

整机结构如图1所示，由风机、空气压缩机、控制电磁阀、静电发生器、柱塞泵、药箱、喷头、机架、行走轮等组成，通过牵引架与拖拉机相连接，动力由拖拉机后动力输出轴通过万向传动轴提供。传动箱的输入轴与万向节连接，经万向节传动轴输出到机具后方的带轮，进而带动空气压缩机、柱塞泵和风机工作。空气压缩机、柱塞泵和风机等组成的主体部分通过底架固接在机架上。主要技术参数见表1。



1. 风机外壳；2. 风机叶轮；3. 风机驱动轴；4. 风机驱动轴座；5. 风机驱动皮带轮；6. 柱塞泵；7. 空气压缩机；8. 空气压缩机驱动皮带轮；9. 机架；10. 支撑轮；11. 支撑轮轴；12. 传动轴；13. 传动箱；14. 联轴器；15. 牵引架；16. 药箱；17. 液位指示器；18. 加水口；19. 控制电磁阀；20. 静电发生器；21. 喷头。

1. Fan covering; 2. Fan impeller; 3. Driving shaft; 4. Shaft seat; 5. Belt wheel; 6. Piston pump; 7. Compressor;8. Belt wheel; 9. Frame; 10. Wheel; 11. Wheel shaft; 12. Transmission shaft; 13. Gearbox; 14. Coupling;15. Traction frame; 16. Spray tank; 17. Level indicator; 18. Injection port; 19. Controlling electromagnetic valve;20. Electrostatic generator; 21. Nozzle.

图1　气力雾化风送式果园静电弥雾机结构图及样机

Fig. 1 Overall structure and prototype of the air-atomized, air-assisted and electrostatic orchard sprayer

表 1 整机主要技术参数

Table 1 Main work parameters of the machine

名称 Name	参数 Parameters
外形尺寸(长×宽×高) Dimensions(length×width×height)/(mm×mm×mm)	2 350×1 420×1 450
配套动力 Matching power/kW	22~45
整机质量 Machine quality/kg	600
作业速度 Work speed/(km·h^{-1})	4~8
药箱容积 Volume of medicine chest/L	1 000
风机形式 Fan form	离心风机 Centrifugal fan
风机转速 Fan speed/(r·min^{-1})	0~2 800
喷雾量 Spray volume/(L·min^{-1})	0~4(液体 Liquid) 0~12(气体 Gas)
喷头数量 Nozzle number	13
喷雾形式 Spray form	扇形雾 Sector spraying
静电发生器电压 Voltage of electrostatic generator/V	12
空气压缩机排量 Displacement of air compressor/(m^3·h^{-1})	10.5
药泵流量 Flow of drug pump/(L·min^{-1})	0~60

2 关键部件的设计

2.1 气流辅助系统的设计

2.1.1 风量的确定 风量的确定遵循置换原则[16]，其原理为喷雾机吹出的带有雾滴的气流，应能驱除并完全置换风机前方直至果树的空间所包容的全部空气。所以设计的喷雾机的风量应大于其置换的空气量，风量的计算公式如下：

$$Q > 2VHLK \quad (1)$$

式中，Q为风机的风量，m^3；V为喷雾机速度，本机取1.5 m·s^{-1}；H为葡萄叶幕高度，1.0~2.0 m；L为喷雾机距离葡萄植株的距离，15.0~25.0 cm；K为气流的衰减和沿途的损失确定的系数，1.1~1.2，本机确定为1.1。将各参数带入公式(1)得Q为0.495~1.650 m^3·s^{-1}。考虑到储备及风量的损失，取Q为1.0 m^3·s^{-1}=3 600 m^3·h^{-1}。

2.1.2 风压的确定 风机的全压包括动压损失和静压损失，而静压损失包括局部压力损失和摩擦压力损失(该机忽略不计)，计算公式如下：

$$p_d=\rho \cdot v^2/2 \quad (2)$$

$$p_j=\zeta \rho \cdot v^2/2 \quad (3)$$

$$p=p_d + p_j \quad (4)$$

式中，p为总压，Pa；p_d为动压损失，Pa；p_j为局部压力损失，Pa；ρ为大气密度，1.29 kg·m^{-3}；V为出口风速，取50 m·s^{-1}；ζ为局部阻力系数，取1.3。经计算，p_d=1 612.5 Pa，p_j= 2 096.25 Pa，p=3 708.75 Pa。对照离心风机风量和风压的设计参数，9-195A离心风机的风量为3 834 m^3·h^{-1}、风压为5 000 Pa，满足设计要求。

2.1.3 出风口数量和尺寸的确定 为了适应葡萄的不同栽培模式，确定弥雾机的出风口为13个，其中两侧各3个，圆弧部分7个。风口总面积计算公式如下：

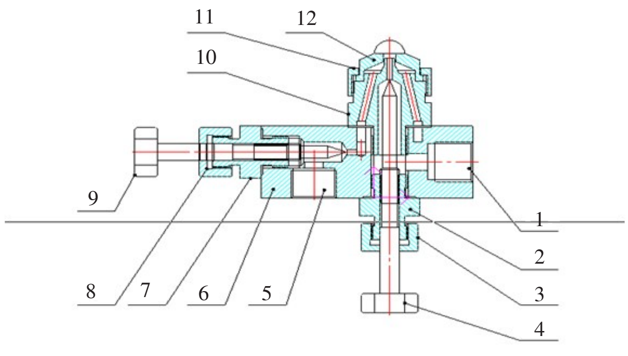
$$S=Q/V \quad (5)$$

式中，S为出风口总面积，m^2；Q为风机风量，1.0 m^3·s^{-1}；V为出口风速，取50 m·s^{-1}，代入公式得S为0.02 m^2，则单个出风口面积为0.02 m^2/13=0.001 5 m^2，考虑其结构位置确定出风口尺寸为20 mm×80 mm。

2.2 气力雾化系统的设计

气力雾化系统的核心部件是气爆雾化喷头和空气压缩机。

2.2.1 喷头的设计 本机采用根据气爆雾化原理设计的球面扇形雾喷头(专利号为ZL 2012 2 0330431.0)，气、液可调，以达到最佳喷雾效果。本喷头在压力2 MPa时，达最大喷雾量4 L·min^{-1}，使用时一般调至0~2 L·min^{-1}。喷头结构见图2。



1. 药液入口；2. 药液流量控制针阀座；3. 药液流量控制针阀座压帽；4. 药液流量控制针阀；5. 气体入口；6. 喷嘴阀体；7. 气体流量控制针阀座；8. 气体流量控制针阀座压帽；9. 气体流量控制针阀；10. 药液喷嘴；11. 混合喷嘴压帽；12. 混合喷嘴。

1. Liquid entrance; 2. Liquid flow control valve seat; 3. Cap of liquid flow control valve seat; 4. Liquid flow control valve; 5. Gas entrance; 6. Valve; 7. Gas flow control valve seat; 8. Cap of gas flow control valve seat; 9. Liquid flow control valve; 10. Liquid nozzle; 11. Cap of mixing nozzle; 12. Mixing nozzle.

图 2 喷头结构图

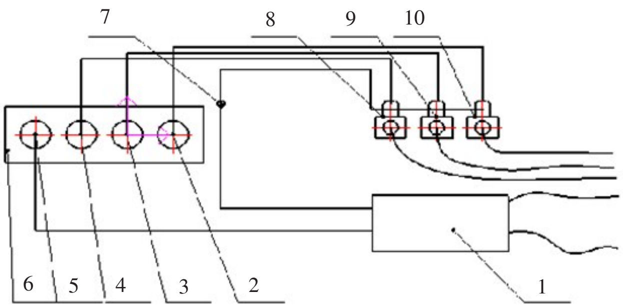
Fig. 2 The structure of nozzle

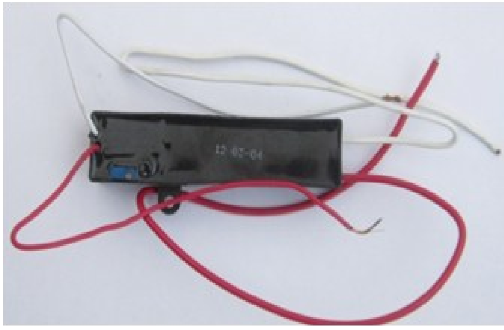
2.2.2 空气压缩机的选型 由于所设计喷头的最大净空气流量为12 L·min^{-1},故13个喷头所需空气压缩机的排量为12×13=156 L·min^{-1}=9.36 m^3·h^{-1},而HX7.5型空气压缩机的排量可达10.5m^3·h^{-1},满足设计要求。

2.3 静电系统的设计

本机的静电系统以拖拉机的蓄电池为电源,选用BSD50-1218高压静电发生器,其供电电压为12~18 V,可产生50~100 kV高压静电,为了防止因高压静电发生器损坏导致工作中断,采用每个喷头配一个高压静电发生器,并联提供高压静电。由于高压静电发生器产生的电压较高,因此对从传动轴、牵引板和行走轮用环氧绝缘板进行绝缘处理,避免了弥雾机由于漏电导致喷药质量下降。

静电系统通过开关控制电磁阀和静电发生器工作。对于V型架和篱架栽培模式,喷雾作业时需闭合静电发生器控制开关和左、右喷雾控制开关,而对于棚架栽培模式,喷雾作业时需闭合静电发生器控制开关、中间喷雾控制开关和左或右喷雾控制开关(具体视机器相对树体位置而定),从而实现了分段、独立喷雾,防止了农药的浪费。静电系统和静电发生器实物如图3所示。





1. 静电发生器; 2. 右喷雾控制开关; 3. 中间喷雾控制开关; 4. 左喷雾控制开关; 5. 静电发生器控制开关; 6. 控制器; 7. 接地公共端; 8. 左喷雾控制电磁阀; 9. 中间喷雾控制电磁阀; 10. 右喷雾控制电磁阀。

1. Electrostatic generator; 2. Right spray switch; 3. Middle spray switch; 4. Left spray switch; 5. Electrostatic generator switch; 6. Controller; 7. Ground terminal; 8. Left spray electromagnetic valve; 9. Middle spray electromagnetic valve; 10. Right spray electromagnetic valve.

图3 静电系统及静电发生器实物

Fig. 3 The electrostatic system and electrostatic generator

3 性能试验

3.1 喷头喷雾量的测定

试验首先测定了喷头的喷雾量,调整喷雾压力分别为0.2 、0.3 和0.4 MPa,测定时间为30 s,用量筒承接喷头喷出的水,试验10次重复。试验结果见表2,当喷雾压力一定时,喷头喷雾量有小幅波动,但差异不大。随着喷雾压力的升高,喷头喷雾量相应增加。

表2 不同喷雾压力下喷头的喷雾量

Table 2 The sprayed capacity of the different pressures

压力 Pressures/MPa	喷雾量 Spray volume /(L·min^{-1})									
0.2	1.00	0.96	0.96	0.98	1.00	0.94	0.93	0.97	0.96	0.98
0.3	1.16	1.20	1.21	1.24	1.22	1.23	1.16	1.18	1.22	1.20
0.4	1.28	1.32	1.32	1.30	1.36	1.33	1.34	1.28	1.30	1.35

3.2 雾滴尺寸的测定

扩散比DR是衡量弥雾机雾化性能好坏的指标。DR值越接近1,表示雾滴的粒径越均匀,一般认为DR值在0.67~1就比较均匀。DR值按公式(6)计算。

$$DR=NMD/VMD \tag{6}$$

式中,NMD为数量中径,即将雾滴群按数量分成相等两部分的雾滴直径,μm;VMD为体积中径,即将雾滴群按体积(直径)分成相等两部分的雾滴直径,μm。

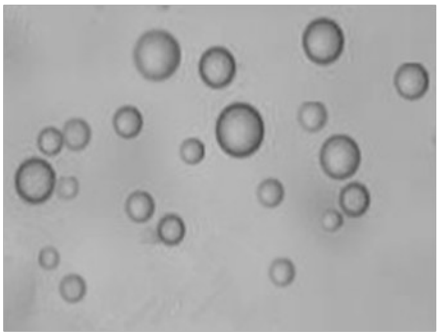
将涂有凡士林和机油(体积比为1:3)的培养皿作为承接器收集雾滴,用于测定雾滴直径。试验中将培养皿距离弥雾机0.4 m处水平匀速通过弥雾区收集雾滴,然后快速测量雾滴直径并拍下照片。试验分别收集了开启和关闭风送系统条件下的雾滴并进行了对比。测定结果如表3所示,当开启该系统

时，VMD为72 μm，NMD为60 μm，由式(6)可知DR为0.83；当关闭该系统时，VMD为110 μm，NMD为80 μm，DR为0.73，说明风送系统提高了雾滴的均匀性。同时结合图4可知，雾滴的整体尺寸相对减小，大部分雾滴的直径在70 μm以下，说明离心风机的二次雾化效果明显。

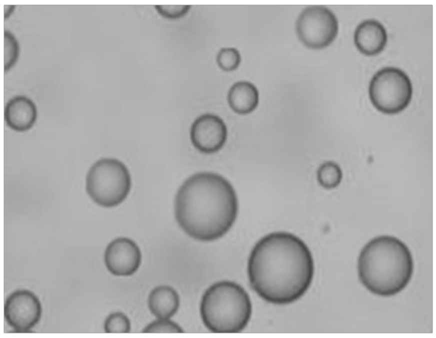
表3 开启和关闭风机的雾滴尺寸

Table 3 The droplet sizes of opening and closing the fan

风机状态 Fan condition	VMD/μm	NMD/μm	DR
开启风机 Starting the fan	72	60	0.83
关闭风机 Closing the fan	110	80	0.73



开启风机 Starting the fan



关闭风机 Closing the fan

图4 开启和关闭风机时雾滴照片

Fig. 4 The droplet photos of starting and closing the fan

4 田间试验

4.1 试验条件

样机的雾滴附着率测定试验于2015年7月13日在中国农业科学院果树研究所葡萄核心技术试验示范园进行。栽培模式为：棚架栽培葡萄株行距0.7 m×4.0 m，树体叶幕厚度和长度分别为0.4 m和3.5 m；V型架栽培葡萄株行距0.7 m×3.5 m，树体叶幕厚度和长度分别为0.4 m和1.4 m，叶幕与地面呈45°倾斜角；篱架栽培葡萄株行距0.7 m×3.5 m，树体叶幕厚度和长度分别为0.4 m和1.4 m。配套动力为40 kW履带拖拉机。

4.2 试验方法

依据NY/T 992—2006《风送式果园喷雾机作业质量》对该机进行试验。对葡萄树设定了测量点：篱架栽培和V型架栽培将叶幕沿铅垂方向设定上、中、下3个测试层面，而棚架栽培将叶幕沿水平方向设定左、中、右3个测试层面，每测试层面分为叶幕外层和叶幕内层。试验时，先将50 mm×80 mm的格纸按测试要求用双面胶黏在测试树定点位置叶片的正反面上，以甲基紫为示踪剂，将溶解好的甲基紫混入盛水药箱中，预混均匀后启动拖拉机，喷头距离树体30 cm，以1.5 m·s^{-1}的作业速度分别在开启和关闭静电系统条件下进行喷洒。

4.3 试验结果

防治病虫害以药液喷布叶片背面为主，叶面正面为辅(图5)，根据这一原则，从表4、表5可知：开启静电系统时，棚架栽培外层叶片正、反面的雾滴平均附着率分别为35.4%和89.4%，内层叶片正、反面的雾滴平均附着率分别为27.5%和71.0%；V型架栽培外层叶片正、反面的雾滴平均附着率分别为92.0%和44.0%，内层叶片正、反面的雾滴平均附着率分别为86.1%和34.4%；篱架栽培外层叶片正、反面的雾滴平均附着率分别为90.7%和41.4%，内层叶片正、反面的雾滴平均附着率分别为72.7%和31.1%；而关闭静电系统时，棚架栽培外层叶片正、反面的雾滴平均附着率分别为30.8%和76.9%，内层叶片正、反面的雾滴平均附着率分别为25.0%和65.4%。V型架栽培外层叶片正、反面的雾滴平均附着率分别为82.0%和40.0%，内层叶片正、反面的雾滴平均附着率分别为80.6%和32.1%。篱架栽培外层叶片正、反面的雾滴平均附着率分别为82.9%和36.8%，内层叶片正、反面的雾滴平均附着率分别为67.7%和

图5 田间试验

Fig. 5 The field experiment

表4　开启静电系统时雾滴附着率

Table 4 The adhesion rates of droplets of opening the electrostatic system

%

层次 Arrgement	位置 Location	篱架栽培 Espalier form cultivation			V型架栽培 V form cultivation			棚架栽培 Trellis form cultivation		
		上 Up	中 Middle	下 Down	上 Up	中 Middle	下 Down	左 Left	中 Middle	右 Right
外层 Outside	正面 Positive side	85.5	93.9	92.7	92.4	92.6	91.0	33.1	36.7	36.3
	背面 Negative side	40.3	43.0	40.8	41.2	44.8	45.9	87.8	91.9	88.5
内层 Inside	正面 Positive side	71.9	73.5	72.8	85.5	88.0	84.8	26.5	28.7	27.2
	背面 Negative side	31.8	30.6	31.0	32.8	35.8	34.6	70.2	72.0	70.9

表5　关闭静电系统时雾滴附着率

Table 5 The adhesion rates of droplets of closing the electrostatic system

%

层次 Arrgement	位置 Location	篱架栽培 Espalier form cultivation			V型架栽培 V form cultivation			棚架栽培 Trellis form cultivation		
		上 Up	中 Middle	下 Down	上 Up	中 Middle	下 Down	左 Left	中 Middle	右 Right
外层 Outside	正面 Positive side	82.5	81.8	84.4	81.1	82.3	82.5	29.8	31.5	31.1
	背面 Negative side	35.7	37.9	36.8	37.8	41.1	41.2	77.4	76.3	77.0
内层 Inside	正面 Positive side	66.9	67.7	68.6	80.1	80.3	81.4	23.0	24.4	27.7
	背面 Negative side	29.8	30.0	29.0	31.2	33.3	31.7	65.2	66.0	64.9

29.6%。开启静电系统使棚架、V型架、篱架栽培葡萄树外层叶片正、反面和内层叶片正、反面雾滴平均附着率分别提高了14.9%、16.3%、10.0%、8.6%，12.2%、10.0%、6.8%、7.3%和9.4%，12.5%、7.4%、5.1%，说明静电系统有效防止了雾滴的飘移，提高了雾滴的附着率。

5　讨　论

根据中国现有葡萄园的栽培模式，设计了一种气力雾化风送式果园静电弥雾机，有效解决了传统植保作业劳动强度大、作业质量差、雾滴易飘移的问题。张晓辉等[17]对风送式葡萄园弥雾机的研究显示，有风送时雾滴数量中径为81.6 μm，体积中径为111.6 μm，雾滴均匀度DR值为0.731；无风送时，雾滴数量中径为108.5 μm，体积中径为169.3 μm，DR值0.641，DR值提高了14%。笔者用水剂油盘法测定了雾滴的尺寸，结果表明，开启风送系统时，雾滴体积中径为72 μm，雾滴数量中径为60 μm，雾滴扩散比DR为0.83，而当关闭风送系统时，雾滴体积中径为110 μm，雾滴数量中径为80 μm，雾滴扩散比DR为0.73，DR提高了13.7%。笔者研制的弥雾机与张晓辉等[17]的研究结果一致，说明风送系统的雾化效果明显，雾滴体积变小且均匀性增加，所测雾滴的尺寸比张晓辉等的研究结果更小，原因归结于除风机的雾化外，主要采用了气力雾化系统即借助空气压缩机产生的高压空气在喷头的反应腔内进行气爆雾化，大大提升了机具的雾化效果；静电系统中雾滴的充电方式分为3种，即电晕充电、感应充电和接触充电[18]，本弥雾机采用的充电方式是接触充电，即高压电极直接接到金属喷头上，这样液体和地之间形成了类似于电容器的2个极板，产生电场，电荷在雾滴上积累，使雾滴带电。这与何雄奎等[19]、杨洲等[20]研究的充电方式选择不同，原因归结于影响充电效果的因素很多，如温度、自然风速及静电电压等，目前对这些具体条件下的研究探讨仍较少。静电喷雾技术的目的是提高雾滴的吸附能力，而本文与何雄奎、杨洲等研究的试验结果均表明雾滴带电使其吸附能力得到了提高；笔者研制的弥雾机开启静电系统使棚架栽培雾滴的外层叶片正、反面和内层叶片正、反面的平均附着率分别提高了14.9%、16.3%和10.0%、8.6%，V型架栽培提高了12.2%、10.0%和6.8%、7.3%，篱架栽培提高了9.4%、12.5%和7.4%、5.1%，与周良富等[21]研制的3WQ-400型双气流辅助静电果园喷雾机静电喷雾与非静电条件相比，临近喷雾机果树外轮廓线（AO）上叶片反面的雾滴覆盖密度提高了20%，而远离喷雾机的果树外轮廓线（BO）上叶面反面雾滴覆盖密度仅提高了7.2%的研究结果相似，说明静电系统有效防止了雾滴的飘移，提高了雾滴的附着率。

6　结　论

气力雾化风送式果园静电弥雾机采用气爆雾化、离心风机的二次雾化和静电吸附防飘移三者结合的喷雾技术，并且能够根据不同的葡萄树体结构

进行分段、独立喷雾，具有明显的创新性。根据气爆雾化原理设计的球面扇形雾喷头和离心风机的二次雾化，使该机雾化效果好、雾滴体积小且均匀，静电吸附提高了雾滴的附着率，有效防止了雾滴的飘移，具有较好的推广应用前景。

参考文献 **References**：

[1] 王海波，刘凤之，王孝娣，翟衡，杜远鹏，张敬国，徐翠云，史祥宾，郝志强．我国果园机械研发与应用概述[J]. 果树学报，2013，30(1)：165-170.
WANG Haibo, LIU Fengzhi, WANG Xiaodi, ZHAI Heng, DU Yuanpeng, ZHANG Jingguo, XU Cuiyun, SHI Xiangbin, HAO Zhiqiang. Review on research, development and application of orchard machinery in China[J]. Journal of Fruit Science, 2013, 30(1): 165-170.

[2] 张盼，吕强，易时来，刘颖，何绍兰，谢让金，郑永强，潘海洋，邓烈．小型无人机对柑橘园的喷雾效果研究[J]. 果树学报，2016，33(1)：34-42.
ZHANG Pan, LÜ Qiang, YI Shilai, LIU Ying, HE Shaolan, XIE Rangjin, ZHENG Yongqiang, PAN Haiyang, DENG Lie. Evaluation of spraying effect using small unmanned aerial vehicle (UAV) in citrus orchard[J]. Journal of Fruit Science, 2016, 33(1): 34-42.

[3] 李超，张晓辉，姜建辉，胡洋洋．葡萄园风送式喷雾机的设计与仿真分析[J]. 山东农业大学学报(自然科学版)，2012，43(4)：555-558.
LI Chao, ZHANG Xiaohui, JIANG Jianhui, HU Yangyang. Design and simulation analysis of the air-assisted vineyard sprayer[J]. Journal of Shandong Agricultural University (Natural Science), 2012, 43(4): 555-558.

[4] 杨洲，牛萌萌，李君，徐兴，孙志全，薛坤鹏．不同侧风和静电电压对静电喷雾飘移的影响[J]. 农业工程学报，2015，31(24)：39-45.
YANG Zhou, NIU Mengmeng, LI Jun, XU Xing, SUN Zhiquan, XUE Kunpeng. Influence of lateral wind and electrostatic voltage on spray drift of electrostatic sprayer[J]. Transactions of the Chinese Society of Agricultural Engineering, 2015, 31(24): 39-45.

[5] 何雄奎．高效施药技术与机具[M]. 北京：中国农业大学出版社，2012.
HE Xiongkui. Efficient pesticide application technology and equipment[M]. Beijing: China Agricultural University Press, 2012.

[6] 张铁，杨学军，严荷荣，王俊，董祥．超高地隙喷杆喷雾机风幕式防飘移技术研究[J]. 农业机械学报，2012，43(12)：77-86.
ZHANG Tie, YANG Xuejun, YAN Herong, WANG Jun, DONG Xiang. Anti-drift technology of super-high clearance boom sprayer with air-assisted system[J]. Transactions of the Chinese Society for Agricultural Machinery, 2012, 43(12): 77-86.

[7] 李超，张晓辉，姜建辉，胡洋洋．葡萄园立管风送式喷雾机的研制与试验[J]. 农业工程学报，2013，29(4)：71-78.
LI Chao, ZHANG Xiaohui, JIANG Jianhui, HU Yangyang. Development and experiment of riser air-blowing sprayer in vineyard [J]. Transactions of the Chinese Society of Agricultural Engineering, 2013, 29(4): 71-78.

[8] 刘秀娟，周宏平，郑加强．农药雾滴飘移控制技术研究进展[J]. 农业工程学报，2005，21(1)：186-190.
LIU Xiujuan, ZHOU Hongping, ZHENG Jiaqiang. Research advances of the technologies for spray drift control of pesticide application[J]. Transactions of the Chinese Society of Agricultural Engineering, 2005, 21(1): 186-190.

[9] 刘雪美，苑进，张晓辉，刘丰乐，李胜奇．3MQ-600型导流式气流辅助喷杆弥雾机研制与试验[J]. 农业工程学报，2012，28(10)：8-12.
LIU Xuemei, YUAN Jin, ZHANG Xiaohui, LIU Fengle, LI Shengqi. Development and experiment on 3MQ-600 type air-assisted boom sprayer with air-deflector[J]. Transactions of the Chinese Society of Agricultural Engineering, 2012, 28(10): 8-12.

[10] DELELE M A, DE MOOR A, VERBOVEN P, ……, NICOLAI L B. CFD modelling of air flow patterns from an air assisted orchard sprayer[J]. Aspects of Applied Biology, 2004, 71(2): 303-310.

[11] ENDALEW M, DEBAERB N, RUTTEN N, ……, VERVBOVEN P. A new integrated CFD modelling approach towards air-assisted orchard spraying. Part I. Model development and effect of wind speed and direction on sprayer airflow[J]. Computers and Electronics in Agriculture, 2010, 71(2): 128-136.

[12] ENDALEW M, DEBAERB N, RUTTEN N, ……, VERVBOVEN P. A new integrated CFD modelling approach towards air-assisted orchard spraying. Part II: Validation for different sprayer types [J]. Computers and Electronics in Agriculture, 2010, 71(2): 137-147.

[13] 王军锋，张娟娟，王贞涛，霍元平，王泽．风幕式气力辅助静电喷雾沉积特性[J]. 农业机械学报，2012，43(2)：61-65.
WANG Junfeng, ZHANG Juanjuan, WANG Zhentao, HUO Yuanping, WANG Ze. Deposition and distribution characteristics of air-assisted electrostatic spraying by wind-curtain[J]. Transactions of the Chinese Society of Agricultural machinery, 2012, 43(2): 61-65.

[14] 张玲，周良富，孙竹，薛新宇，秦维彩．双风道风送静电喷雾系统试验研究[J].中国农机化学报，2014，35(6)：65-68.
ZHANG Ling, ZHOU Liangfu, SUN Zhu, XUE Xinyu, QIN Weicai. Experimental study on a double duct air assisted electrostatic spraying system[J]. Journal of Chinese Agricultural Mechanization, 2014, 35(6): 65-68.

[15] 贾卫东，胡化超，陈龙，陈志刚，魏新华．风幕式静电喷杆喷雾喷头雾化与雾滴沉积性能试验[J]. 农业工程学报，2015，31(7)：53-59.
JIA Weidong, HU Huachao, CHEN Long, CHEN Zhigang, WEI Xinhua. Performance experiment on spray atomization and droplets deposition of wind-curtain electrostatic boom spray[J]. Trans-

actions of the Chinese Society of Agricultural Engineering，2015，31(7):53-59.

[16] 戴奋奋．风送喷雾机风量的选择与计算[J]. 植物保护，2008，34(6)：124-127.
DAI Fenfen. Selection and calculation of the air-blowing sprayer [J]. Plant Protection，2008，34(6):124-127.

[17] 张晓辉，王亮杰，侯存良，李岩磊，冯海明．风送式葡萄园弥雾机的设计与试验[J]. 中国农机化学报，2016，37(7)：57-61.
ZHANG Xiaohui，WANG Liangjie，HOU Cunliang，LI Yanlei，FENG Haiming. Development and experiment of air- assisted vineyard sprayer[J]. Journal of Chinese Agricultural Mechinanization，2016，37(7):57-61.

[18] 沈从举，贾首星，汤智辉，周艳，孟祥金，苑立强．农药静电喷雾研究现状与应用前景[J]. 农机化研究，2010，32(4)：10-13.
SHEN Congju，JIA Shouxing，TANG Zhihui，ZHOU Yan，MENG Xiangjin，YUAN Liqiang. Research actuality and application prospects of pesticide electrostatic spraying[J]. Journal of Agricultural Mechanization Research，2010，32(4):10-13.

[19] 何雄奎，严苛荣，储金宇，汪健，曾爱军，刘亚佳．果园自动对靶静电喷雾机设计与试验研究[J]. 农业工程学报，2003，19(6)：78-80.
HE Xiongkui，YAN Kerong，CHU Jinyu，WANG Jian，ZENG Aijun，LIU Yajia. Design and testing of the automatic target detecting，electrostatic，air assisted，orchard sprayer[J]. Transactions of the Chinese Society of Agricultural Engineering，2003，19(6):78-80.

[20] 杨洲，牛萌萌，李君，徐兴，许绩彤，陈兆春．果园在线混药型静电喷雾机的设计与试验[J]. 农业工程学报，2015，31(21)：60-67.
YANG Zhou，NIU Mengmeng，LI Jun，XU Xing，XU Jitong，CHEN Zhaochun. Design and experiment of an electrostatic sprayer with on-line mixing system for orchard[J]. Transactions of the Chinese Society of Agricultural Engineering，2015，31(21)：60-67.

[21] 周良富，张玲，薛新宇，丁为民，孙竹，周晴晴，崔龙飞．3WQ-400型双气流辅助静电果园喷雾机设计与试验[J]. 农业工程学报，2016，32(16)：45-53.
ZHOU Liangfu，ZHANG Ling，XUE Xinyu，DING Weimin，SUN Zhu，ZHOU Qingqing，CUI Longfei. Design and experiment of 3WQ- 400 double air- assisted electrostatic orchard sprayer[J]. Transactions of the Chinese Society of Agricultural Engineering，2016，32(16)：45-53.