基于高频电磁阀的脉宽调制变量喷头喷雾特性

李龙龙[1],何雄奎[1※],宋坚利[1],仲崇山[2]
(1. 中国农业大学理学院,北京 100193;2. 中国农业大学信息与电气工程学院,北京 100083)

摘 要:为探究基于高频电磁阀的变量喷雾特性,该研究采用高频、对信号快速响应的电磁阀设计了高于20 Hz的脉宽调制(pulse width moderation, PWM)变量喷雾系统;针对农业施药作业上常用ST标准扇形和IDK防飘喷头,测试了不同频率和占空比对流量、雾滴粒径、雾化过程、纵向沉积分布均匀性的影响。结果表明,在高频下,流量与占空比呈线性关系,随着频率的增大,流量线性区间减小,增大压力和频率,可以有效增大流量调节倍数,30 Hz时最大可达10倍;PWM喷雾时,瞬间雾滴粒径发生周期性变化,增大频率,雾滴体积中值中径(volume medium diameter,VMD)平均值受占空比的影响变小,占空比增大,VMD有减小的趋势,对于ST110-02号喷头各频率下VMD从占空比20%~100%下降了100 μm;沉积试验中,频率和占空比都会影响沉积均匀性,对于IDK120-04号喷头,占空比为40%时,30 Hz下的C.V(coefficient of variation)值较15 Hz减小了6.07%;15 Hz时,IDK120-02和04号喷头在占空比40%到100%变异系数分别下降了11.75%和18.31%;30 Hz时,两喷头在占空比40%到100%变异系数分别下降8.72%和12.24%,并且,ST喷头沉积均匀性优于IDK喷头。该研究为高频电磁阀在PWM变量施药系统中的应用及参数选择提供理论基础。

关键词:喷雾;农业机械;喷头;高频电磁阀;变量施药;雾化;沉积;流量
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0 引 言

随着人们对农药环境污染及食品安全的日益重视,基于按需喷药的变量施药技术正在成为植保领域的重点发展方向[1]。目前,变量施药控制主要有以下3种:压力调节式、浓度调节式和PWM(pulse width modulation)间歇喷雾流量调节式[2],其中,基于PWM的喷雾流量调节系统由于反应时间短,响应速度快、流量调节范围大,且使用常规喷头即可获得良好的喷雾特性而受到越来越多研究人员的关注[3-5]。1990年Giles等人首次利用电磁阀和一个标准喷头组合实现变量喷雾并测试了固定频率下雾滴大小和雾化状态[3]。随后的二十多年里,研究人员对PWM在变量施药技术上的应用做了大量的研究工作,Giles等人在1997年试验发现通过改变占空比和压力可以得到固定的雾滴粒径[6];John研究了在10 Hz频率下,不同占空比的喷雾质量评价,研究发现在较低的占空比下雾滴中径的变化最大,并且<100 μm的可飘失雾滴百分比最大[7];Lebeau等人设计了基于喷杆速度变化的PWM变量施药控制系统,并对此控制系统进行试验测试,最终选定试验所用占空比为16 Hz[8-9];Pierce Robert等人研究频率为16 Hz,不同占空比下的沉积特性,试验发现纵向沉积变异系数在占空比100%时为10%,25%占空比时为65%[10],说明改变占空比会影响喷雾沉积均匀性。在国内PWM变量施药研究时间相对较短,随着人们对现代精准农业的重视,PWM变量施药研究也日趋增多[11-24]。其中,翟长远等人设计了PWM变量控制系统,在2~10 Hz频率下试验得出了喷头流量模型,参数检验和失拟检验表明喷头流量模型合适[25];邓巍等人分析讨论了PWM间歇式脉动变量喷雾在10 Hz频率以下的雾化特性[26]。这些研究均在低频条件下进行。

实际上,较高的PWM频率是喷雾覆盖连续性的保证[8],可以提高纵向沉积分布均匀性,尤其在高速作业的情况下。因此,本文在高频电磁阀的基础上设计了PWM变量控制系统,

可根据工况需求改变频率和占空比,通过开展流量、雾滴粒径、雾化过程、沉积分布均匀性与频率、占空比的关系诸方面的研究,了解高频电磁阀在PWM变量喷雾中的雾化特性,分析高频电磁阀在PWM变量施药中的适用性,以期为高频电磁阀在PWM变量施药系统中的应用提供理论基础。

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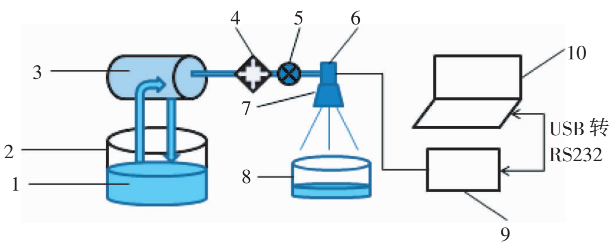
作者简介:李龙龙(1989-),博士生,主要从事植保机械与施药技术研究。北京 中国农业大学理学院,100193。Email:lizefeng1219@126.com
※通信作者:何雄奎(1966-),教授,博士生导师,主要从事植保机械与施药技术研究。北京 中国农业大学理学院,100193。
Email:xiongkui@cau.edu.cn

1 材料与方法

1.1 PWM 变量喷雾系统

PWM 变量喷雾系统由 12 V 电源、驱动、单片机、电磁阀、喷头体、计算机、串口通信模块组成，利用计算机实时改变频率和占空比，从而达到变量施药的目的，控制界面如图 1a。计算机模拟信号发生器，通过 USB 转 RS232 转换线与单片机连接，计算机发出指令后通过单片机将信号传输给电磁阀。变量喷雾系统中使用的电磁阀为压缩天然气（compressed natural gas，CNG）高频电磁阀，电磁阀的性能如表 1 所示，喷雾试验系统如图 1b。

a. PWM 变量喷雾控制系统界面
a. Interface of PWM variable spray control system



b. PWM 喷雾系统
b. PWM spray system

1.药液 2.药罐 3.隔膜泵 4.调压阀 5.压力表 6.高频电磁阀 7.喷头 8.接液器 9.PWM 信号发生及传输模块 10.计算机

1.Pesticide 2.Tank 3.Diaphragm pump 4.Pressure regulating valve 5.Pressure gage 6.High frequency electromagnetic valve 7.Nozzle 8. Measuring cylinder 9. PWM waveform generator and transmission module 10.Computer

图 1 PWM 变量控制喷雾系统
Fig.1 PWM variable spray control system

表 1 高频电磁阀参数
Table 1 Parameters of high-frequency electromagnetic valve

项目 Items	数值 Values
使用寿命 operation life/亿次	>10
线圈电阻 coil resistance/kΩ	2.5±0.375
工作电压 working voltage/V	12±1.8
最小脉冲 minimum pulse width/ms	1.3±0.065
关闭时间 turn-off time/ms	0.9±0.045
开启时间 turn-on time/ms	0.9±0.045
工作温度 operating temperature/℃	−30~120
最高频率 maximum frequency/Hz	167

1.2 流量测试

理论上讲，喷雾压力和频率一定时，喷头流量与占空比成正相关。为了验证试验中所用高频电磁阀是否符合这一规律，在 0.2~0.5 MPa 喷雾压力、不同频率和占空比工况下测量不同喷头的流量。

试验用喷头为德国 Lechler 公司生产的标准扇形雾喷头 ST110-02，ST110-03，ST120-04，频率范围为 12~37 Hz，占空比范围为 20%~100%。试验用自来水作为试验液体。每次测量中，秒表记录喷雾时间（30 s），万分之一天平测量 30 s 内液体重量，进而算得喷头流量（L/min），每次试验重复五次，最后得到测试条件下的流量平均值并根据公式（1）求得流量调节倍数 P。

$$P=\frac{q_{x=100}-q_{x=20}}{q_{x=20}} \tag{1}$$

式中 P 为流量调节倍数；$q_{x=100}$为占空比 100%时的喷头流量，L/min；$q_{x=20}$为占空比 20%时的喷头流量，L/min。

1.3 雾滴粒径测试

采用英国 Malvern 公司生产的 Spraytec 雾滴粒径分析仪定点测量雾化区的雾滴粒径，将喷头置于雾滴粒径分析仪的正上方 50 cm 处，该仪器可测试连续一定时间段（比如 10 s）的粒径，也可每秒 0~500 Hz 断续测量某一间隔时间内的雾滴粒径。由于 PWM 变量喷雾为断续喷雾，因此采用连续（10 s）和间断（100 Hz）两种测量模式探究雾滴粒径与 PWM 参数（频率和占空比）的关系，本文采用体积中值中径（volume medium diameter，VMD）计量雾滴粒径。

将 Spraytec 分析仪的测量模式设为连续测量 10 s，试验压力定为 0.3 MPa，分别测量 ST110-02，ST110-03，ST120-04 3 种喷头的雾滴粒径，PWM 喷雾系统频率分别为 15、20、25、30、35 Hz，占空比从 20%~100%每隔 5%做一个设置。每个测试重复 3 次，得到 VMD 平均值。非连续间断测量试验中，将 Spraytec 分析仪设为间断测量模式，测量频率设为 100 Hz，即每秒钟测量 100 次，其他试验参数与连续测量一致。

1.4 喷头雾化区的可视化研究

为了进一步研究 PWM 变量喷雾的雾化特性，压力 0.3 MPa 下，使用高速摄影仪对喷头雾化区进行整体动态视频拍摄并保存。高速摄影仪拍摄帧数为 3000FPS，快门速度 1/4 000 s；PWM 控制系统频率为 15、25 和 30 Hz，占空比为 25%、50%和 75%。试验喷头为 ST110-02，ST110-03 和 ST120-04，利用文献[27]中介绍的方法进行拍摄，拍摄完成后将保存的视频转换成图像，不同工况下观察 PWM 变量喷雾雾化特性，试验用中国农业大学饮水系统中自来水作为试验液体。

1.5 纵向沉积测试

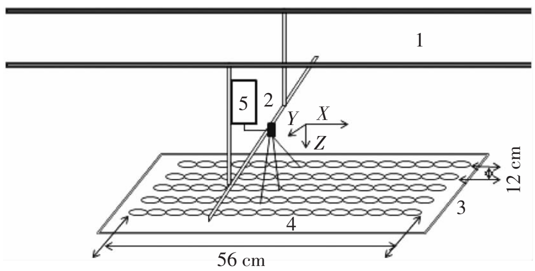
1.5.1 测试平台

为了测试和分析基于高频电磁阀的 PWM 变量施药的沉积特性，在中国农业大学药械与施药技术实验室设计了基于喷雾天车的 PWM 喷雾沉积测试平台，如图 2 所示，装有喷头的喷杆固定在天车上，喷头正下方放一雾滴收集台用以放置雾滴收集器，喷头与收集台的垂直距离为 0.5 m，试验中用直径 35 mm 的塑料培养皿作为雾滴收集器，平行放置 5 列，相邻间隔 12 cm，每一列紧密排列 16 个培养皿（0.56 m），第 3 列放置于喷头 X 轴正下方。

1.5.2 沉积测试

3‰柠檬黄溶液作为示踪剂，测试结束后迅速盖上培养皿盖，将培养皿放置于黑箱内，防止光照引起柠檬黄分

解。试验选取 15 Hz 和 30 Hz 2 个频率,占空比分别设置为 40%、70%、和 100%,天车运行速度为 2 m/s,喷雾压力为 0.3 MPa,试验所用喷头为常规扇形雾喷头 ST110-02,ST120-04 和防飘喷头 IDK120-02,IDK120-04。每个试验重复 3 次。试验结束后,培养皿内加 3.5 mL 去离子水洗脱、震荡,最后用分光光度计测量吸光度,利用文献[28]中介绍的方法求得沉积量(mL/cm²),最终根据沉积量求得纵向平均变异系数(coefficient of variation,C.V)值。



1.喷雾天车 2.喷头 3.收集台 4.雾滴收集器 5.PWM 控制器
1. Travelling boom 2.Nozzle 3. Spray bench 4. Spray collectors 5. PWM controller

图 2　PWM 喷雾沉积测试平台
Fig.2　Platform for spray deposition test

2　结果与讨论

2.1　喷头流量

通过 3 种喷头的流量测试显示,基于高频电磁阀的 PWM 变量喷雾的喷头流量与频率和占空比有关,在一定的压力和频率下,流量开始随着占空比成线性正相关,达到一定占空比之后流量不再增长,喷头流量与占空比的关系为 $q=a\cdot x+b$,q 为喷头流量(L/min);a,b 为常数,x 为占空比。图 3 是 ST120-04 号喷头在各工况下的流量变化。

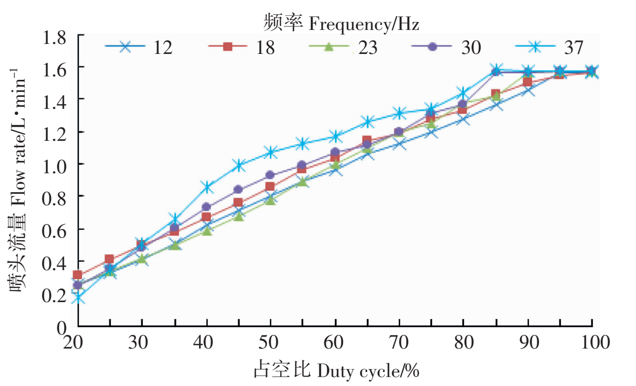
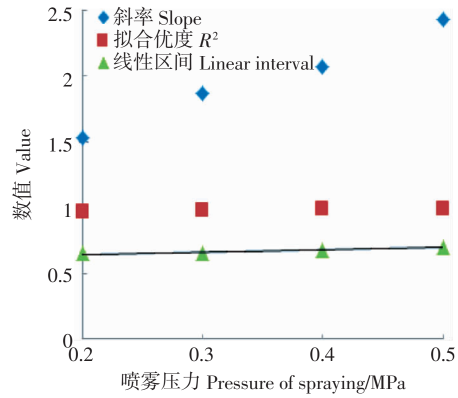
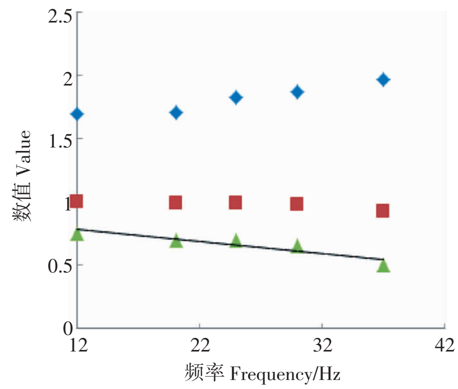


图 3　0.3 MPa 压力下 ST120-04 喷头流量与频率和占空比的关系
Fig.3　Relationship between flow rate and frequency and duct cycle under pressure of 0.3 MPa

将试验得到的流量数据进行拟合,图 4a、4b 分别为 ST120-04 号喷头在 30 Hz 频率和 0.3 MPa 喷雾压力下流量拟合直线斜率、R^2、线性区间(线性区间为流量与占空比成正相关关系的占空比范围,如占空比在 20%~80%时喷头流量成线性正相关则线性区间为 0.6 的变化。可以看出压力和频率变化对流量变化拟合度影响较小;与频率变化相比,喷雾压力变化能够更有效的调节喷头流量,且线性区间变化相对较小。



a. 压力的影响
a. The influence of Pressure



b. 作业频率的影响
b. The influence of Frequency

图 4　作业参数和拟合直线斜率、R^2、线性区间的关系
Fig.4　Relationship between working parameter and slope, R^2 and interval linear

根据公式(1)求得 ST120-04 号喷头的流量调节倍数,如图 5。压力一定时,流量调节倍数随着频率的增大呈现增大的趋势,这种趋势在压力大时比较明显,30 Hz、0.5 MPa 工况下流量倍数可达 10,流量调节范围对实际作业有指导性意义,根据流量调节倍数和作业需要,选取合适的频率和喷雾压力来达到作业要求。

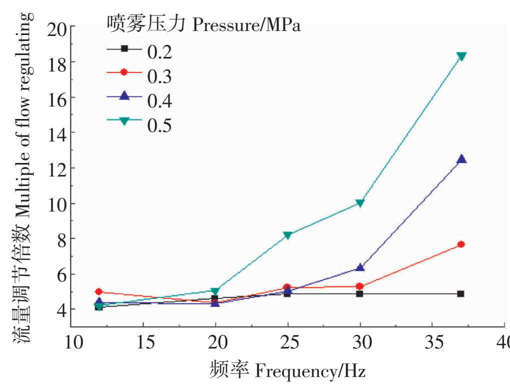
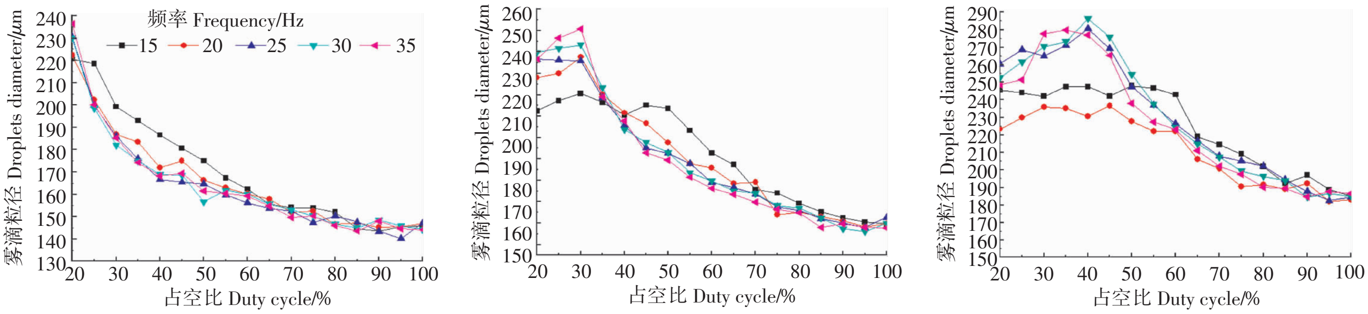


图 5　作业参数与流量调节倍数关系
Fig.5　Relationship between working conditions and flow regulation

2.2　雾滴粒径

图 6 分别为 3 种喷头不同压力,连续 10 s 测量雾滴粒径随频率和占空比的变化关系。从图中可以看出,3 种喷头雾化区的雾滴粒径总体上随占空比的增大而减小,占空比达到 60%后,各频率下的粒径曲线几乎趋于一致。ST110-03 和 ST120-04 号喷头的粒径在占空比较小时先

增大，最后出现和 ST110-02 号喷头相同的变化趋势，这是由于 03 和 04 号喷头形成雾化区所需的流量较大，在较小占空比时，由于流量较小不能形成完整的雾化区而产生大雾滴。



a. ST110-02 号喷头
a. Nozzle of ST110-02

b. ST110-03 号喷头
b. Nozzle of ST110-03

c. ST120-04 号喷头
c. Nozzle of ST120-04

图 6 连续测量模式下 3 种喷头雾滴粒径与占空比、频率的关系

Fig.6 Relationship between particle diameter and duty cycle and frequency of three species of nozzles in continuous measurement mode

0.3 MPa 压力下 ST120-04 号喷头在非连续测量模式下的测试结果如图 7 所示，测试时的 PWM 参数为频率 15 Hz，占空比 50%，测试时间为 0.4 s，正好对应 6 个 PWM 周期。从图中可以看出，雾滴粒径随着 PWM 的变化呈现周期性变化，在平均值 252 μm 上下不断变化，这说明 PWM 喷雾过程中雾滴粒径会发生明显的改变。造成这种现象的原因是电磁阀快速开闭造成的湍流和压力不稳定。为了进一步探究频率和占空比对雾滴粒径的影响，在100 Hz 测量模式下分别测量 15 Hz 和 30 Hz 下 3 个占空比的雾滴粒径，试验结果如表 2 所示，用方差表示每个工况下的雾滴粒径的变化浮动。进一步研究发现，增大频率和占空比可以减小雾滴粒径的变化，并且各个工况下的雾滴粒径平均值与连续测量模式下的试验结果一致。

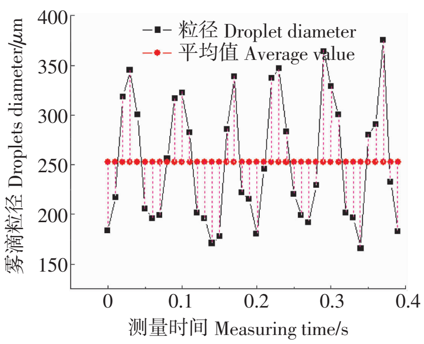


图 7 100 Hz 测量模式下 ST120-04 号喷头雾滴粒径与测量时间关系

Fig.7 Relationship between particle diameter and measure time of ST120-04 nozzle in measure mode of 100 Hz

表 2 不同工况下雾滴粒径的变化

Table 2 Changes of particle diameter under different working condition

频率 Frequency/Hz	项目 Items	占空比 Duty cycle/%		
		50	75	100
15	方差 Variance/μm	65.65	42.19	12.48
	粒径平均值 Average droplets diameter/μm	252.3	228.5	188.6
30	方差 Variance/μm	39.66	33.26	9.69
	粒径平均值 Average droplets diameter/μm	259.5	202.1	190.7

2.3 喷头雾化区的可视化分析

为了进一步探究试验 2.2 中雾滴粒径的变化，利用文献[24]的方法对喷头雾化区进行高速摄影分析，发现 PWM 变量喷雾过程中由于电磁阀瞬间开闭会导致雾化带断裂，表 3 给出的是不同频率下喷头雾化带断裂时最大占空比，对于 ST110-02 号喷头，各个工况下雾化带断裂时占空比均小于 20%；ST120-04 号喷头的断裂占空比最大，这是由于该型号喷头流量最大，因此雾化带断裂时的最大占空比也较大。此外，通过图片发现喷头雾化区断裂瞬间，喷嘴下方 50 cm 处会产生大雾滴，这也解释了连续测量模式下各个喷嘴雾滴粒径曲线变化的原因，由于较小占空比时流量较小，ST110-03 和 ST120-04 号喷头雾化带断裂导致大雾滴产生，因此雾滴粒径有先增大后平缓减小的趋势。

表 3 不同喷头雾化带断裂时的占空比

Table 3 Duty cycle at fracture of nozzle atomization area

喷头类型 Type of nozzle	频率 Frequency/Hz				
	15	20	25	30	35
	雾化区断裂时的占空比 Duty cycle at fracture of nozzle atomization area/%				
ST110-02	<20	<20	<20	<20	<20
ST110-03	43	34	30	28	26
ST120-04	60	51	42	38	35

2.4 纵向沉积特性

图 8 为 0.3 MPa 压力下，IDK-04 号喷头在 15 Hz，占空比 40%、70%和 100%下纵向沉积变化，从图中看出纵向沉积量呈现出周期性的变化规律。表 4 是 15 Hz 时 3 个占空比下流量和沉积量，流量平均值（40%:70%:100%）=1:1.73:2.29，沉积量平均值（40%:70%:100%）=1:1.43:1.76。

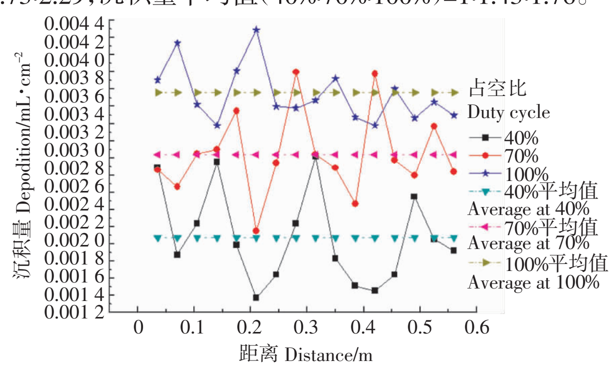


图 8 IDK-04 号喷头在行驶方向上沉积量变化示意图

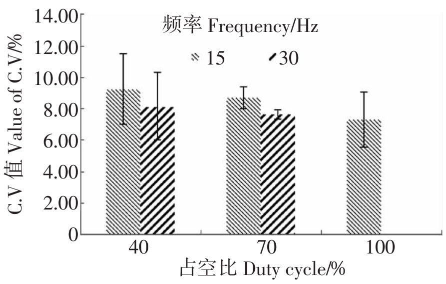
Fig.8 Schematic of deposition quantity on travelinging direction of IDK-04

表 4　IDK-04 号喷头在不同占空比下的流量与沉积量

Table 4　Flow rate and deposition quantity in different duty cycle of IDK-04

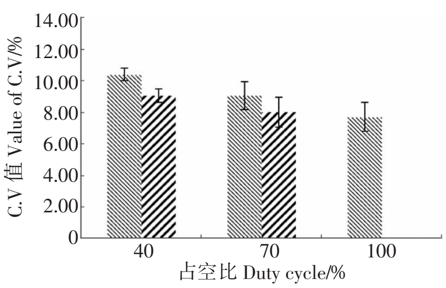
项目 Items	占空比 Duty cycle/%		
	40	70	100
流量 Flow rate/(L·min^{-1})	0.68	1.18	1.56
沉积量 Deposition/(mL·cm^{-2})	0.21	0.30	0.37

图 9 分别为 ST110-02 和 04、IDK120-02 和 04 喷头在 15 Hz 和 30 Hz,各占空比的 C.V 值,从图中可以看出,PWM 变量喷雾的沉积受频率和占空比的影响,同一占空比,高频下的纵向 C.V 值比低频下的小,对于 IDK120-04 号喷头,占空比为 40%下,15 Hz 时的 C.V 值为 28.31%,30 Hz 时的 C.V 值为 22.24%,减小了 6.07%;相同频率下,随着占空比的增大,C.V 值有减小的趋势,15 Hz 时,IDK-02 和 04 号喷头从占空比 40%到 100%分别下降了 11.75%和 18.31%;30 Hz 时,IDK-02 和 04 号喷头从占空比 40%到 100%分别下降了 8.72%和 12.24%。因此在 PWM 变量喷雾系统中,高频是沉积均匀性的保证,不仅要考虑流量的变化范围,也要考虑到占空比的选择范围,低占空比时会增大沉积不均匀性的几率。



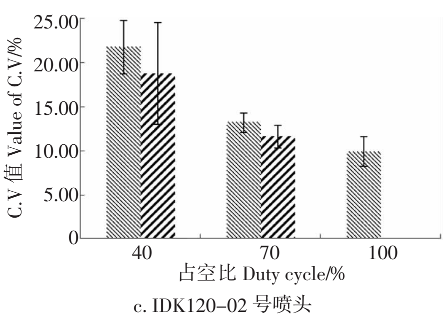
a. ST110-02 号喷头

a. Nozzle of ST110-02



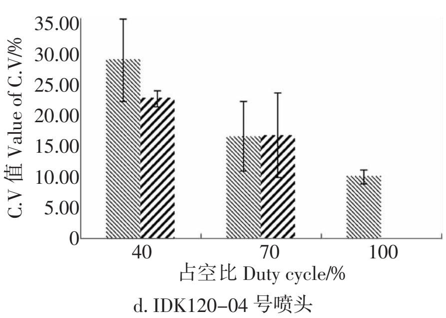
b. ST120-04 号喷头

b. Nozzle of ST120-04



c. IDK120-02 号喷头

c. Nozzle of IDK120-02



d. IDK120-04 号喷头

d. Nozzle of IDK120-04

图 9　4 种喷嘴在不同工况下的 C.V 值

Fig.9　C.V-value in different working condition of four nozzles

相比于 IDK 喷头,ST 喷头的纵向沉积均匀性相对较好,C.V 值都在 10%左右,随频率和占空比的影响较小。但也呈现出和 IDK 喷头一样的趋势,频率大的沉积均匀性较低频的好,随着占空比增大,沉积均匀性有变好的趋势,C.V 值变化相对平缓。

3　结论

1)基于高频电磁阀的 PWM 变量喷雾,对于标准扇形雾喷头,在压力和频率一定时,流量和占空比呈线性关系,线性区间随频率增大逐渐减小,增大压力和频率可有效增大流量调节范围。

2)采用 PWM 变量喷雾时,瞬间雾滴粒径发生周期性的变化;VMD 在平均值附近以正弦波上下浮动,增大频率和占空比,可以减小雾滴粒径的变化。

3)由于 PWM 变量喷雾的工作特性会导致喷头雾化区雾化带断裂,并且不同类型喷头在不同频率下雾化带断裂的最大占空比不同,ST-110-02 号喷头在各频率下占空比都小于 20%,ST120-04 号在 15 Hz 时的最大,为 60%。雾化带断裂瞬间会产生大雾滴,导致雾滴粒径瞬间增大。

4)PWM 频率和占空比影响雾滴沉积,增大占空比和频率能够提高雾滴沉积均匀性。

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Spray characteristics on pulse-width modulation variable application based on high frequency electromagnetic valve

Li Longlong[1], He Xiongkui[1※], Song Jianli[1], Zhong Chongshan[2]

(1. *College of Science, China Agricultural University, Beijing* 100193, *China*; 2. *College of Information and Electrical Engineering, China Agricultural University, Beijing* 100083, *China*)

Abstract: High frequency solenoid valve has the advantage of fast response, and it can effectively improve the deposition uniformity especially for high-speed operation. In order to study the variable spraying characteristics of high frequency solenoid valve, a pulse width modulation (PWM) variable rate spraying system based on high frequency solenoid valve was developed. The minimum pulse width of the solenoid valve used in the research was 1.3 ms. The PWM variable rate spraying system was made up of power supply, drive, single chip microcomputer, solenoid valve, serial communication module, computer, and so on. Frequency and duty cycle of solenoid valve could be regulated by the PWM control system in real time. This article applied the ST standard fan nozzle and IDK anti-drift nozzle which are commonly used in the agriculture to carry out experiment, which focused on how frequency and duty cycle of solenoid valve influenced flow rate, droplet diameter, atomization process and longitudinal deposition uniformity. In the flow rate test, 12~37 Hz and 20%~100% were chosen as the working frequency and duty cycle and the working pressure was 0.2~0.5 MPa. The water weight was measured by precision balance in 30 s to get flow rate (L/min), and each test was repeated 5 times. It was observed that the flow rate had a linear relation with the duty cycle in the fixed working pressure and the R2 of regression line was greater than 0.9 at 12~37 Hz. Linear interval was 0.8 at 12 Hz and 0.56 at 37 Hz, and it was concluded that the linear interval decreased with the increasing of frequency. For the nozzle of ST120-04 under the working condition of 0.4 MPa and 30 Hz, the flow rate increased by 6 times at duty cycle of 100% compared to 20%, while the flow rate increased by 10 times in the pressure of 0.5 MPa. Therefor it was essential to collect proper frequency and spraying pressure to meet working requirement. In the article, 2 measurement modes of Spraytec particle sizer were chosen in the test of droplet diameter. The continuous measurement mode could measure the droplet diameter continuously for 10 s. Droplets could be measured discontinuously at the measure frequency of 100 Hz which meant that droplets were measured for 100 times in one second by the Spraytec particle sizer. The frequency and duty cycle were 15~35 Hz and 20%~100% and the working pressure was 0.3 MPa. Nozzle was fixed at 50 cm above the Spraytec particle sizer and volume medium diameter (VMD) was used to describe the droplet diameter in the article. The results showed that in the continuous measurement mode, the droplet diameter decreased from 20% to 100% respectively for the nozzle of ST110-02, ST110-03 and ST120-04. Moreover, for ST110-03 and ST120-04, the droplet diameter increased from 20% to 40%, because these 2 nozzles needed more flow rate to form the atomization zone yet the flow rate was too small from 20% to 40%. In the discontinuous measurement mode, the droplet diameter changed periodically and the average VMD of 3 nozzles was consistent with the test result of continuous measurement mode. In order to further research the atomization characteristics of PWM variable spraying system based on the high frequency solenoid valve, high-speed camera was used to observe the atomization zone at different frequency and duty cycle. The frame and shutter of high-speed camera were set in 3 000 FPS and 1/4000 s respectively. It was observed that the atomization zone would break up because of nozzle´s instantaneous open-close. The duty cycles at the fracture of atomization zone were 26%~43% and 35%~60% for the ST110-03 and ST120-04 nozzle from 15 to 35 Hz. Deposition test bench based on the traveling boom was developed in the Center of Chemical Application Technology, China Agricultural University. Petri dishes (35 mm) were used to collect droplets. The collectors were set in 5 parallel columns and the interval of adjacent 2 columns was 12 cm. Each column contained 16 Petri dishes and the 3rd column was placed under the traveling direction of nozzle. Tartrazine (3‰) was chosen as the tracer material and spray boom speed was 2 m/s. In the deposition test, 15 and 30 Hz, and 40%, 70% and 100% were chosen as the working frequency and duty cycle. The results showed that frequency and duty cycle would influence deposition uniformity. For the IDK120-04 nozzle at duty cycle of 40%, the CV (coefficient of variation) at 30 Hz decreased by 6.07% compared with 15 Hz. From 40% to 100%, CV decreased by 11.75% and 18.31% respectively for IDK120-02 and IDK120-04 at 15 Hz while decreased by 8.72% and 12.24% respectively at 30 Hz. Also, the deposition uniformity of ST standard nozzle was better than the IDK anti-drift nozzle. These results show that the high frequency solenoid valve can be used in the PWM variable rate spraying system and it has advantage in longitudinal deposition uniformity.

Keywords: spraying; agricultural machinery; nozzles; high frequency electromagnetic valve; variable spray application; atomization; deposition; flow rate