Enhancement of droplets quality for fog cooling system in a naturally-ventilated greenhouse using centrifugal and axial fans

Handarto¹, D R Kendarto¹, M Saukat¹, T Herwanto¹, K Pandiangan¹

¹Department of Agricultural Engineering and Biosystem, Faculty of Agro-industrial Technology, Universitas Padjadjaran, Bandung, Indonesia
²Corresponding author, e-mail: handarto@unpad.ac.id

Abstract. A fog cooling system (FCS) is applied to maintain the desired air temperature and humidity in a greenhouse. For the effective application of this system, sizes of fog particles belonging to the criteria of less than 60 μm in diameter and its uniformity are important parameters that need to be achieved. The objective of this research is to analyze usage of centrifugal and axial fans in order to enhance quality of fog particles that generated through 0.1-mm nozzles. Horizontally installed nozzles with both centrifugal and axial fans to create finer and more uniform fog particles was compared with horizontal nozzles with centrifugal fans only and with axial fans only. The centrifugal fans are installed 80 cm in front of nozzles while the axial fans are installed behind nozzles. The sizes of fog particles resulted by centrifugal fan, axial fan, and both axial and centrifugal fans are 11.90 μm, 5.28 μm and 2.69 μm, respectively. The use of both fans produces the most delicate fog particles. Electricity consumption for both fans is the smallest compare to the other electrical appliances on FCS (relay, pump, pressure release valve). Additional electricity power consumption per hour due to the use of both fans is 25 W.

1. Introduction
A fog cooling system (FCS) is one of the evaporative cooling methods developed to create optimum conditions for temperature and humidity in the greenhouse during the summer [1-3]. The concept of FCS is sensible heat conversion to latent heat through evaporation of water in the fog particle size range (diameter less than 60 μm) which is sprayed in the air in a greenhouse to increase its contact surface area with air [4,5]. According to [6], compared to two other evaporative cooling methods (pad-and-fan cooling system and mist cooling system), FCS has a comparative advantage, namely: 1) generated fog particles are finer so that the evaporation efficiency is higher without wetting the foliage; and 2) the distribution of fog particles to all parts of the greenhouse is faster so that the affected air temperature and humidity are more evenly distributed. Size and uniformity distribution of fog particles become important parameters. The finer and more uniform size of the fog particles can create the faster and more uniform temperature and humidity changes in all part of the greenhouse. Installing a fan to the nozzle not only can reduce the size of the droplet, but also can spread the droplet to all parts of the greenhouse.

Studies of fan usage for FCS in greenhouses have been carried out by many researchers. Decrease and uniformity of temperature resulted by FCS and its comparison with the mist cooling system were analyzed [7]. Changes in temperature and relative humidity produced by FCS in a natural ventilated...
greenhouses were analyzed [2]. Using of upward air stream to improve greenhouse cooling performance was analyzed [8]. However, in these studies, evaluation of horizontally installed nozzles with fan on size and uniformity of fog particles has not been reported.

Quality (size and uniformity) of fog particles is an important factor. Fine and uniform fog particles cause changes in temperature and humidity in the greenhouse to be faster and more uniform. Not only can reduce the size of the fog particles, the use of fans can also spread the particles evenly to all parts of the greenhouse. The fans used are centrifugal fans and axial fans. Centrifugal type fans have high pressure and low air flow, while axial type fans have low pressure but produce high air flow. An axial fan circulates air along its rotating axis. Air pressure originates from the aerodynamic motion of the rotating blade [9]. The purpose of this research is to produce droplets that meet fog criteria and its uniformity using centrifugal and axial fans.

2. Material and Method

2.1. Preliminary Experiment

Preliminary experiment was carried out inside a room with a floor size of 6m x 6m. All doors and windows are closed hermetically so there is no air movement inside the room. An air flow velocity inside the room is below 0.25 m.s$^{-1}$. Centrifugal fans are installed 80 cm in front of the nozzle and are the same height as the axial fans. Horizontally installed nozzles with both axial and centrifugal fans to create finer and more uniform fog particles was compared with horizontal nozzles with axial fans only and with centrifugal fans only. The axial fans are installed behind nozzles while the centrifugal fans are installed 80 cm in front of nozzles. Water sensitive papers (WSP) (Teejet Technologies, Spraying Systems Co., Switzerland) are placed under nozzles with distances of 60 cm (h1), 70 cm (h2), 80 cm (h3), and 90 cm (h4) (figure 1). The position of WSP and the fans against the nozzles for each treatment is presented in figure 1. The FCS is activated for 60 s then the diameter of the droplet at the WSP are measured.

2.2. Main Experimental (Inside a Greenhouse)

The experiment consisted of two stages: preliminary and main. The preliminary experiment was carried out in a room while the main research was carried out in a greenhouse. The room dimension was 3 m x 4 m x 3 m. All doors and windows are closed so there is no air movement occurred in the room. 0.1 mm, 0.2 mm and 0.3 mm nozzles are alternately installed face down with a slope of 45° at height of 120 cm (h4) from the floor.

The main experiment is carried out during the day in the Greenhouse D (single-span, type of monitor, dimension 8 m x 8 m x 6 m) in the Experimental Field and Greenhouses of Universitas
Padjadjaran, Jatinangor Campus. During the experiment, the side ventilators are closed and the roof ventilator is fully opened. Inside the greenhouse, tomato plants are cultivated in pots.

2.3. Installation of FCS
The components in the installation of the fog cooling system consist of a nozzle (ø = 0.1 mm and 0.3 mm), solenoid valve (Tiangong Uni-D AC 220 V Model UZ-A), fogging pump (working pressure 1.2 MPa) and electromagnetic relay (Omron MK2P AC 220V 8 Pin 10A). The cooling system consists of 12 nozzles (brass material, for PE hose 6 mm) which are installed horizontally on the pipe frame. Four nozzles are installed each on the right side, the middle and the left side of the pipe frame. Height of nozzle is 300 cm from floor with a nozzle distance of 0.75 m (figure 3). These nozzles are connected through a PE hose tied to a pipe frame (PVC material, diameter of 0.5 in).

2.4. Fogging mechanism
After filtered with a filter, water is flowed to the storage tank. The fogging pump sucks in water and then flows through the delivery hose (PE material, 6 mm in diameter) to the nozzle. Finally, through
the nozzle orifice, fog particles are sprayed into the air in the greenhouse. In the preliminary and main experiments, the fogging pump was operated for period 60 s, separated by interval of 240 s.

2.5. Measurement Method

Size and uniformity of the fog particle generated by the nozzle are observed after the FCS is activated. The presence of a fog particle was identified through WSP that placed above the tomato plants canopy, at 12 observation location. Furthermore, WSP was detected using Axio Imager A2 Automatic Analizer Electron Microscope.

Fog particle uniformity level was calculated using equations (1) to (5).

\[
\bar{X} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (1)
\]

\[
SD = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{X})^2}{n-1}} \quad (2)
\]

\[
SD_{Ix} = \frac{SD}{\sqrt{n_{treatment}}} \quad (3)
\]

\[
UCL = \bar{X} + kSD \quad (4)
\]

\[
LCL = \bar{X} - kSD \quad (5)
\]

Where:

\( \bar{X} \) = mean value of fog particle diameter

SD = standardized deviation from a group of fog particle diameter

SD\(_{Ix}\) = standardized deviation from one data taken from a group of fog particle diameter

UCL = Upper Control Limit (the uppermost range of data)

LCL = Lower Control Limit (the lowest data range limit).

Value of coefficient of variant (CV) was calculated using equation (6).

\[
CV = \frac{SD}{\bar{X}} \times 100\% \quad (6)
\]

The consumption of electrical energy by each component in the FCS (relay, pump, pressure release valve, centrifugal fan, and axial fan) is measured using a clamp meter.

3. Result and Discussion

Fog particles caught by WSP at each observation location are presented in figure 4. At all observation location, the color of the WSP after the use of centrifugal fans, axial fans and both fans, getting to the right become brighter.
Figure 4. Images of WSP caught fog particles at each observation location.

This shows that the number of fog particles (NFP) caught by the WSP resulting from the use of centrifugal fans, axial fans and both fans, sequentially are smaller (See figure 5). As well as diameter of fog particle (DFP), the use of centrifugal fans, axial fans and both fans, sequentially results in finer particles.

![Figure 5. Average of number and diameter of fog particle resulting from the use of fans.](image-url)
Data from the fog particles uniformity test results in the range of 0-60 µm are presented in figure 6.

![Figure 6](image)

**Figure 6.** Fog particles uniformity test results in the range of 0-60 µm.

From various treatments, the ability to reduce the diameter of the particle completely was in the range of the fog category <60 µm, but there was still a difference in the height of the graphs for each treatment. The difference in height of the graph represents the size of the diameter of the fog particle from the results of the measurement of the diameter of the droplet on the WSP. Furthermore, the level of uniformity of the actual combined treatment was carried out in the greenhouse, where the value of the UCL and the LCL were known from the calculation results, namely the range 4.12-9.13 µm.

The use of centrifugal fans produces 10 points that are in the control line level of uniformity and only 2 points are outside the control line namely G and H points, but both points are not bad because they are still below the control boundary line. Ideally, the smaller and uniform the diameter of the droplet, the more uniform the microclimate change in the greenhouse. The smallest diameter droplet size is at point G which is 3 µm and the biggest point is at point A which is 7.41 µm.

The use of axial fans produces only 3 points that are in the control line level of uniformity, namely points H, K, and L. The rest is outside the control line for uniformity. The smallest diameter droplet size is at point L that is 8.19 µm, while the largest droplet is at point J which is 16.21 µm.

The use of both centrifugal and axial fans produces only 1 point that is within the control boundary line, point B. That is, almost all points of droplet diameter measurement results on WSP are under 4.12 µm. The largest droplet size is at point B which is 6.81 µm and the smallest point is at point H which is 0.74 µm. Meanwhile, for testing the level of droplet uniformity, the use of the two fans is the best to reduce the diameter of the droplet diameter. The calculation and graph above show that the average of each subgroup is between the UCL and the LCL, so the fog particle size data obtained is uniform.

The consumption of electrical energy for each component of FC is presented in Figure 7. When FCS is not operating (off, for 310 min), FCS components that are using electrical energy are relay and pressure release valve. Meanwhile, when FCS is operating (on, for 62 min), FCS components that are using electrical energy are relay, pump and fans. The total electricity consumption when FCS off (6,094.29 kJ) is greater than when FCS on (6,002.34 kJ). Additional electricity power consumption per hour due to the use of both fans is 25 W.
4. Conclusion
Base on the experimental studied on the enhancement of the droplet quality fog cooling system it can be concluded that:

a) The system employing a nozzle with both of centrifugal and axial fans can create finer and more uniform fog particles.

b) The average diameter of the treated droplet (a) centrifugal fan, (b) axial fan, and (c) both axial and centrifugal fans are 11.90 μm, 5.28 μm and 2.69 μm, respectively.

c) The electrical energy consumed by axial and centrifugal fans in the fog cooling system is the smallest compared to other electronic components, namely 29.68 kJ and 62.27 kJ.

d) The electrical energy consumption before and after the addition both of centrifugal and axial fans are 6,002.34 kJ and 6,094.29 kJ, respectively.

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