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Spray curtains as devices for surface spraying during the SARS-CoV-2 pandemic

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ABSTRACT

Counteracting the spread of the SARS-CoV-2 virus is a current and important problem. A crucial issue in this area is the disinfection of various surfaces, as well as the air itself. For this purpose, devices such as foggers, which have different designs, are used. The appropriate size of droplets and their distribution determines the effectiveness of disinfectants. The paper presents droplet size distributions and characteristic mean droplet diameters, which are obtained with the use of a conical pressure-swirl atomizer. For the purpose of the analysis, the laser diffraction method was used. The influence of gas pressure and the distance from the atomizer on the spray angle and the distance between the nozzles on the spray curtain was also demonstrated.

1. Introduction

The atomization of liquids is used in many areas, including combustion and firefighting (Gai et al., 2021; Panchasara and Ashwath, 2021). The most important parameters that determine the suitability of a given atomizer, and also the effectiveness of the atomization process, include the distribution of droplet sizes and the equivalent diameters of the droplets, among which the Sauter mean diameter is the most popular (Ochowiak et al., 2021; Justlin et al., 1995; Wan et al., 1995). The SARS-CoV-2 coronavirus pandemic affected the health care and economy. It was necessary to introduce some changes in the functioning of society and the production of new vaccines (Ho et al., 2021; Khater et al., 2021; Schoenmaker et al., 2021). Also disinfection of both surfaces and air has become a very important issue. For this purpose, the main devices are various types of atomizers that are often included in other apparatus. Foggers, which are currently very popular, are used to disinfect flat surfaces in hospitals, schools or workplaces, but are also used to disinfect clothing or protective masks (Albert et al., 2021; Ochowiak et al., 2019). Another device that can be an effective solution in the fight against SARS-CoV-2 are spray curtains, which involve atomizers working together.

Spray curtains are modern solutions that are used both in the public sector and by private users. The principle of their operation is based on placing some kind of water curtain in the path of a harmful gas or heat stream in order to dilute the stream of pollutants or to weaken the heat stream. They are used in firefighting and mining, and can also be utilized to reduce the risk coming from various sources in order to cool or trap harmful compounds (dusts, gases) from the air and to limit their spread. Their use allows the effects of toxic and hazardous compounds to be controlled and mitigated. Water curtains are effective when absorbing, diluting and dispersing heavy gases. They have a simple structure, and are characterized by their high efficiency, reliability, low price and universal application. Due to the contact of the water curtain with the gas phase, processes of heat, mass and momentum exchange may occur. As a result of the contact of the water curtain with the gas phase, its dilution takes place, and if it contains toxic compounds, they are absorbed by the droplets. In the case of various types of industrial apparatus, curtains constitute a kind of filter that absorbs and suppresses the radiation that could significantly affect the operation of the installation. Water curtains also allow the effects of fires in industrial installations to be mitigated (Cai et al., 2020). Spray curtains are recognized as one of the most economical and promising methods of controlling LNG vapor clouds. The effectiveness of a water curtain depends, among other things, on the type and spacing of the used nozzles, the pressure, and the height at which the nozzles are mounted. The most commonly used are full cone pressure atomizers, as well as two-phase atomizers with a conical pressure-swirl atomizer.

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atomizers (Haldia et al., 2005). The paper (Buchlin, 2017) presents the modeling of a spray curtain that was used as thermal protection, as well as to dilute a stream of pollutants. The simulation results are in line with the experimental results. In the case of a heat shield, greater efficiency was obtained with smaller droplets, higher water pressure, a larger surface of the liquid (to counter the radiation), and a greater density of the nozzles’ distribution. The shock-wave configuration also performed better when compared to the vertical arrangement of the nozzles. The action of the curtain significantly reduced the concentration of pollutants in the gas phase. The curtain was a good solution during low wind speeds of up to 5 m/s. Under specific conditions, there was a suitable curtain height and nozzle geometry, which enabled a compromise between gas entrainment and air velocity to be obtained.

Qi et al. (Qi et al., 2016) presented the results of research concerning the use of water curtains for preventing the release of CO₂. The CO₂ release rate was 120 l/h. Two types of spray nozzles (a fan spray nozzle and a conical nozzle) were used during the research. They were placed 1.5 m from the CO₂ and a conical nozzle) were used during the research. They were placed 1.5 m from the CO₂ emission source, and were mounted on a movable pipe at a distance of 0.6 m from each other at a height of 1.6 m. The water pressure was 0.1 MPa. As a result of the operation of the atomizers, the water streams decomposed into droplets and caused air entrainment at the border of the water curtains. Water gave momentum to the surrounding air so that the air could reduce the amount of CO₂.

The curtains’ efficiency was approximately 80%, with the efficiency of the fan spray nozzle being about 0.6% higher than the conical nozzle. The effectiveness of single and double water curtains was also compared. Single curtains were more effective – by about 1.7%–than double curtains. The operation of the water curtains was most effective when the nozzles were located at a height of 1.2 m. A positive effect of an increased pressure on the removal of CO₂ was observed, whereas an increase of the distance between the nozzles and the CO₂ emission source deteriorated the efficiency of the process. The CO₂ flow rate caused a reduction in the effectiveness of the curtains’ operation.

Seaman et al. (2020) analyzed the use of water curtains for removing coal dust (FCD) generated in underground mines, which may cause an explosion. The water curtain used in the study consisted of three collectors, each of which allowed for seven nozzles at a distance of 0.15 m from each other to be mounted. Full cone sprays were used. The operating pressure was 1103 kPa, which corresponded to a flow rate of 3.8 l/min. It was observed that the water curtain did not cause a significant dust migration due to air disturbance, and therefore spraying was concentrated in areas with a high dust concentration. Sauter mean diameters ranging from 95 to 125 μm, and a range of speed of the droplets from 4 to 15 m/s, were obtained. It should be noted that results may vary, depending on where the droplets are measured. It was also shown that larger droplets of sprayed water are more likely to interact with airborne dust, causing it to fall out of the ventilating air. Larger droplets will also sink faster than droplets with smaller diameters. A curtain equipped with 21 nozzles provided a smaller number of drops when compared to one consisting of 18 nozzles.

Water curtains can also be used to reduce the concentration of LNG (liquid natural gas) vapor clouds. This is due to a number of mechanisms (mechanical, dilution and thermal), which involve the entraining of the air by the spray generated by the water curtains, the diluting of the water vapor by the floated air, and the transferring of the heat and air by the spray generated by the water curtains, the diluting of the water vapor by the floated air, and the transferring of the heat and momentum to the gas clouds. Water curtains reduce the concentration of LNG and also heat the mixture of air and LNG vapors (Seaman et al., 2010a, 2010b). Two types of nozzles were taken into account in paper (Rana et al., 2010a, 2010b) full cone and fan flat. A full cone atomizer causes greater turbulence closer to the spray area, which in turn increases the intensity of mixing the gas clouds with the air. A fan flat atomizer creates a solid barrier in the path of the LNG cloud, causing it to flow upwards. This results in a reduced concentration at the level of the ground. Each of the used types of nozzles has a different flow pattern and a different size of drop-lecs.
Fig. 1. The atomizer applied in the research: a) 3D model, b) cross-section with internal dimensions, c) nozzle installed in the experimental set-up, d) external dimensions.
droplets scatter laser light. The scattered light is then measured using a system of more than 30 detectors. Each individual detector collects scattered light within the appropriate range of angles, and also has a separate data channel. In the next step, the recorded scatter image is converted by means of a system of detectors into an electrical signal, which in turn is further processed by electronic circuits (analog and digital) and sent to a computer. It is worth noting that the analysis of light scattering is performed using an appropriate optical formula. On the basis of the obtained measurement results, the droplet size distribution is calculated. Apart from the distribution of the droplets, the characteristic mean droplet diameters were also determined. The most commonly used mean diameter is the Sauter mean diameter ($D_{32}$, SMD), which is described by the following relation (Lefebvre and McDonell, 2017; Orzechowski and Prywer, 2008):

$$D_{32} = \frac{\sum_{i=1}^{n} D_i n_i}{\sum_{i=1}^{n} D_i^3 n_i}$$  \hspace{1cm} (1)$$

Droplet diameters marked using e.g. symbols $D_{v(50)}$, $D_{v(10)}$, and $D_{v(90)}$ can be found in literature. Diameter $D_{v(50)}$ determines exactly 50% of the droplets’ distribution [4] in terms of their mass and number. Diameter $D_{v(10)}$ indicates that 10% of the liquid volume consists of droplets with diameters smaller than $D_{v(10)}$. In turn, parameter $D_{v(90)}$ defines that 90% of the liquid volume consists of droplets with diameters smaller than $D_{v(90)}$. The measure of the homogeneity of the spray is the difference between these diameters. In addition, the paper specifies the spray angle of the liquid - this angle is extremely important with regards to the arrangement of the nozzles on the spray boom - i.e. the distance between them on the curtain’s frame.

3. Results

The evaluation of the efficiency of the spraying device mainly depends on the distri-bution of the diameter of the sprayed aerosol droplets. Figs. 2–5 show the mean droplet distributions, which were obtained for different distances from the sprayer at a constant gas pressure of 3 bar. On the basis of the obtained results, it can be seen that the peak of small droplets disappears with an increase in the distance from the atomizer. This is most likely caused by the evaporation of the droplets as the distance (drop path) increases. This is reflected in the values of the mean droplet diameters. For example, for a constant pressure of 3 bar, $D_{32} = 28.62 \mu m$ at a distance of 0.5 m, and $D_{32} = 34.64 \mu m$ at a distance of 1 m. The obtained histograms are left-skewed.

Figs. 5–8 show histograms for the various pressures, with a constant distance from the sprayer equal to 1 m. The increase in the pressure caused a decrease in the volume share of the largest droplets that had diameters of above 100 $\mu m$ and, consequently, a shift of the histograms to the left. At the same time, a significant increase in the proportion of smaller droplets (up to 20 $\mu m$) can be observed. It is also visible in the obtained values of the mean droplet diameters. At a constant distance from the sprayer of 1 m, and with pressure within the range of 3–6 bar, the Sauter mean diameter decreases from 34.64 $\mu m$ to 16.44 $\mu m$.

Tables 1 and 2 present a summary of the characteristic parameters of the droplets. It can be observed that at a constant pressure, with increasing distance from the atomizer, higher values of mean diameters $D_{v(10)}$, $D_{v(50)}$, $D_{v(90)}$, $D_{43}$ and $D_{32}$ were obtained. For example, for a pressure of 6 bar, $D_{v(50)}$ at a distance of 0.5 m was equal to 18.77 $\mu m$, while at a distance of 1 m it was equal to 23.27 $\mu m$. In turn, the mean droplet diameters decreased with an increase in the pressure. The pressure effect was much greater than the change in the distance from the atomizer. At a distance of 1 m, the diameter of $D_{v(50)}$ decreased from 53.33 $\mu m$ to 23.27 $\mu m$, with an increase in the pressure from 3 to 6 bar. Under the same conditions, the diameter of $D_{v(43)}$ decreased from 68.13 $\mu m$ to 28.21 $\mu m$. These results are closely related to the respective droplet diameter distributions. Therefore, changing the operating conditions allows diameters in a wide range of sizes to be obtained. Thanks to this, it is possible to adjust the scope of the sprayer’s operation to specific applications, depending on the user’s needs.

An important parameter is the spray angle, which often determines the height of the curtain’s support beam/frame on which the nozzles are placed above the sprayed surface. The spray angle, although most often given by the manufacturer as a constant value in a specific sprayer design, in fact changes with changes in pressure. The greater the pressure of the liquid, the greater the angle. However, this variation mostly applies to standard flat fan atomizers, rather than to two-phase atomizers. In the former, the pressure of the liquid is decisive, whereas in the latter it is the pressure of the liquid, the gas, and the design of the atomizer. Fig. 9 shows a visualization of the spray angle for the pressures of 3 and 6 bar. The visualization of the spray angle obtained by averaging all registered images in a measurement series for the pressures of 3 and 6 bar. The analysis of the value of the angle was performed using Image-Pro Plus 6.1 by MediaCybernetics Inc. (USA). As can be seen in the proposed design of the atomizer, the influence of the pressure within the assessed range on the spray angle is small, e.g. for 3 bar it is 22.5°, and for 6 bar it is 21°. The accuracy and deviations of the spray angle values were within ±1°. When arranging the nozzles on the beam, it was assumed that the spray angle was not less than 20°, and therefore:

$$\tan(20°) = \frac{l}{x}$$  \hspace{1cm} (2)$$

where $l$ is the distance from the atomizer, and $x$ is the distance between

Fig. 2. The distribution of the mean droplet diameters obtained at a distance of 0.25 m from the atomizer at a pressure of 3 bar.
Relatively large distances reached by the droplets mean that the supporting structure, i.e. the curtain’s frame, can be far from the sprinkled surface (Fig. 10), which in turn translates into its versatility. A larger curtain allows the sprinkling/disinfection of larger vehicles, which is also thanks to the large range of the stream of smaller droplets.

Fig. 3. The distribution of the mean droplet diameters obtained at a distance of 0.50 m from the atomizer at a pressure of 3 bar.

Fig. 4. The distribution of the mean droplet diameters obtained at a distance of 0.75 m from the atomizer at a pressure of 3 bar.

Fig. 5. The distribution of the mean droplet diameters obtained at a distance of 1 m from the atomizer at a pressure of 3 bar.
4. Conclusions

The study analyzed the effect of gas pressure and the distance from the orifice on both the distribution of droplet diameters and the characteristic mean diameters. These are important values when assessing the suitability of a given spray device for disinfection. A two-phase
A conical pressure-swirl atomizer was used in the research. On the basis of the obtained results, the disappearance of the smallest droplets was observed with an increase in the distance from the discharge of the nozzle in the atomizer, which was most likely caused by the evaporation of the droplets over a longer distance. This was confirmed by the values of the mean droplet diameters, which increased with an increase in the distance from the atomizer’s orifice. Increasing the gas pressure from 3 to 6 bar resulted in a decrease in the proportion of droplets with the largest diameters, and a decrease in the characteristic values of the mean droplet diameters. Moreover, the spray angle was determined, and the distribution of the nozzles on the curtain’s support frame was analyzed.

Table 1
The results obtained during the measurements for distance x = 0.5 m

| Parameter          | P = 3 bar | P = 4 bar | P = 5 bar | P = 6 bar |
|--------------------|-----------|-----------|-----------|-----------|
| Trans (%)          | 63.7      | 54.9      | 70.5      | 62.6      |
| $D_{v10}$ (μm)     | 12.2      | 8.477     | 7.235     | 6.342     |
| $D_{v50}$ (μm)     | 54.05     | 44.45     | 26.9      | 18.77     |
| $D_{v90}$ (μm)     | 138.3     | 138.5     | 68.67     | 47.46     |
| $D_{43}$ (μm)      | 66.28     | 61.08     | 33.14     | 23.35     |
| $D_{32}$ (μm)      | 28.62     | 22.92     | 17.03     | 13.36     |
| Span               | 2.333     | 2.925     | 2.284     | 2.191     |
| $\%V < 5$ μm (%)   | 1.728     | 2.171     | 2.72      | 3.213     |
| $\%V < 10$ μm (%) | 7.619     | 12.94     | 18.7      | 29.56     |

Table 2
The results obtained during the measurements for distance x = 1 m.

| Parameter          | P = 3 bar | P = 4 bar | P = 5 bar | P = 6 bar |
|--------------------|-----------|-----------|-----------|-----------|
| Trans (%)          | 72.9      | 75.1      | 78.3      | 84.9      |
| $D_{v10}$ (μm)     | 17.09     | 10.36     | 8.44      | 7.61      |
| $D_{v50}$ (μm)     | 56.33     | 41.72     | 29.07     | 23.27     |
| $D_{v90}$ (μm)     | 135.3     | 107.8     | 72.51     | 55.96     |
| $D_{43}$ (μm)      | 68.13     | 51.82     | 35.69     | 28.21     |
| $D_{32}$ (μm)      | 34.64     | 24.31     | 19.01     | 16.44     |
| Span               | 2.099     | 2.337     | 2.204     | 2.078     |
| $\%V < 5$ μm (%)   | 0.917     | 1.807     | 2.485     | 2.646     |
| $\%V < 10$ μm (%) | 4.383     | 9.444     | 13.5      | 17.19     |

Fig. 9. The spray angle for a pressure of: a) 3 bar; b) 6 bar.

Fig. 10. Dependence between the distance between the nozzles and the distance of the nozzles from the sprayed surface.

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