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Review

Fogging for the disinfection of food processing factories and equipment

D. Burfoot*, K. Hall†, K. Brown† and Y. Xu*

***Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS, UK (Tel.: +44-1525-860000; fax: +44-1525-861697; e-mail: dean.burfoot@bbsrc.ac.uk, yongfu.xu@bbsrc.ac.uk)**

†Campden and Chorleywood Food Research Association, Chipping Campden, Gloucs GL55 6LD, UK (Tel.: +44-1386-842000; fax: +44-1386-842100; e-mail: k.hall@ccfra.co.uk, k.brown@ccfra.co.uk)

Disinfectants are commonly applied as fogs in the chilled food industry. Recent research has shown that fogging is effective in reducing the number of organisms on upward-facing surfaces but, in general, it is not effective on vertical or downward-facing surfaces. Fogging also reduces the number of viable airborne organisms, although the reason for this decrease in not understood. Numerical models of the dispersion of airborne particles have been used to simulate the fogging process. These models, with supporting experiments, showed that fogs should be most effective when the median diameter of the fog droplets lies between 10 and 20 μm. Droplets in this size range disperse well and settle within about 45 min. This gives good coverage and the fog clears from the air quickly enough not to pose major disruption to factory operations.

Fogs consisting of small droplets of disinfectant are applied after cleaning and sanitisation in food factories to ensure that all regions of the food processing factory and equipment have received an application of disinfectant. Disinfection is not a substitute for thorough cleaning — it is an additional safeguard. Fogging has also been used to reduce the counts of airborne viable microorganisms which may have come from low care areas, people, the fabric of the building, or have been produced as aerosols during cleaning. The process, whereby a fog is produced through nozzles, is used quite widely by chilled foods manufacturers especially in high care environments such as salad, sandwich, ready meal and dairy processing. It is also applied in many environments including freezers, chillers, ripening rooms for cheeses and meats, process lines, and production and assembly areas.

Despite the quite widespread use of disinfectant fogging in the food industry, most research has been carried out for the medical and pharmaceutical industries and the conclusions from that research have often been contradictory. McRay *et al.* [1] considered the use of fogging in hospitals. They used a 2000 ppm active concentration of a quarternary ammonium formulation to achieve a 99.99% reduction in microbial counts on walls, floors and in the air (the latter was inferred using test surfaces suspended from the ceiling). However, Darlow [2] concluded that on the whole fogging was unsatisfactory in fermentation laboratories, Edwards [3] also reported on the ineffectiveness of fogging operating rooms and Daschner *et al.* [4] suggested that fogging has only 'ritualistic value'. Little research has been carried out concerning applications in the food industry, one exception being the work by Hedrick *et al.* [5] who found that a chlorine fog reduced the airborne count of organisms. However, Holah *et al.* [6] found that fogging was uncontrollable and ineffective compared with other disinfection methods, such as the application of ozone or use of ultraviolet radiation.

More recently, research has been carried out with support under the UK Advanced and Hygienic Manufacturing LINK Programme to answer questions regarding the application of disinfectant fogs in food processing environments.

Is disinfectant fogging effective on surfaces?

Tests were carried out to assess the action of fogged disinfectants on bacteria on surfaces. The action on biofilms, where the organisms are attached to the surface within a protective extracellular matrix, was not studied as cleaning operations should be used to remove such material. Bacteria were attached to test surfaces using the following procedure.

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An overnight culture was centrifuged in an MSE Mistral 2000 centrifuge at 4500 rpm for 11 min. The supernatant was discarded and the pellet resuspended in 100 ml of phosphate buffer (34 g KH_2PO_4, 500 ml distilled water, adjusted to pH 7.2 with NaOH and made up to 1000 ml). The suspension was then placed onto sterile stainless steel coupons (100×40×1.5 mm thick sheet) and allowed to attach for 1 h. The buffer allows attachment but no growth of organisms. The excess suspension was aspirated off and the coupons dried in a controlled cabinet at room temperature.

The coupons were located at various positions within a room and exposed for 15 min to a chemical fog produced by a twin fluid nozzle. The disinfectant consisted of 1% solution of the commercial product Quatdet® which contains a quarternary ammonium compound. After treatment, the coupons were analysed in the following way.

The coupons were swabbed into maximum recovery diluent (LabM: LAB 103) and inactivator (30 ml polysorbate 80, 30 g saponin, and 3 g lecithin made up to 1000 ml with distilled water). The inactivator stops the action of the disinfectant.

Fig. 1 shows a typical spatial variation of the effectiveness of fogging. In this example, the steel coupons were suspended at various locations within the room and Fig. 1 shows the log reductions in microorganisms measured at those locations. The largest reductions occur directly in front of the nozzle and close to the floor. This is to be expected as these are the regions where the flux of chemical is greatest.

Gravity is an important force affecting the deposition of chemical and consequent reductions in microbial counts. Tests were carried out with the coupons located horizontally or vertically and with the organisms attached to the top or bottom surfaces of the coupons. On average, the ratio of reduction of microorganisms was in the order of 2100 (upward-facing surface): 110 (vertical surface): 1 (downward-facing surface). Smaller effects of orientation were found close to the nozzle because some droplets in that region would deposit by direct impaction (like a spray) and there was a very high concentration of droplets. Orientation of the test surface was most important further away from the nozzle where little chemical deposited on to vertical and downward facing surfaces. For effective disinfection of vertical and downward facing surfaces, application techniques other than conventional fogging need to be used. Spraying and electrostatic fogging are two possibilities to improve coverage on to such surfaces.

Air movement is also important as this affects the dispersion of the droplets. Fig. 2 shows that the use of a fan can increase the number of organisms killed on surfaces because it provides a better dispersion of the chemical. However, in practical situations the use of fans can be difficult partly due to the need to operate the fans in a very moist environment and also because factory staff need to locate the fan prior to fogging. In well-designed fogging systems, with an adequate number of nozzles, there should not be a need to use fans to assist dispersion.

Fig. 3 shows that the reduction in microbial counts increases with the amount of disinfectant applied by fogging up to a limit at which no more viable organisms are present. Further increases in the amount of chemical applied could have no further effect. It is important to determine the amount of chemical required, better still the amount of active ingredient, to achieve the required results.

Is disinfectant fogging effective on airborne organisms?

Airborne counts in food production areas can vary widely. A survey of 39 factories showed a range of mean airborne counts of 1500–8000 cfu/m^3 [7]. Worfel *et al.*

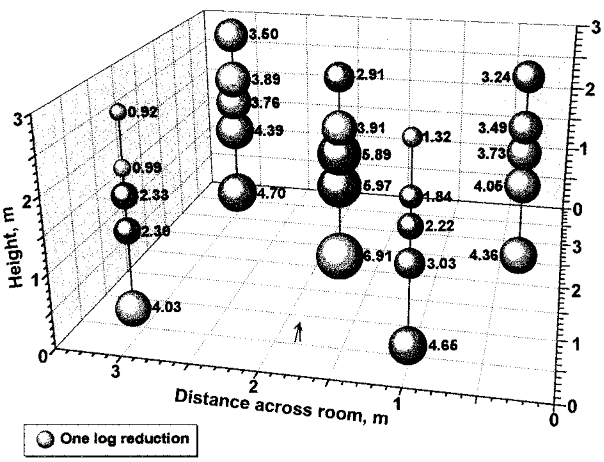


Fig. 1. Spatial variation of log reductions in microorganism counts on stainless steel coupons suspended horizontally in a room. The volume of each sphere is proportional to the log reduction at that position. The arrow shows the position and direction of the fogging nozzle.

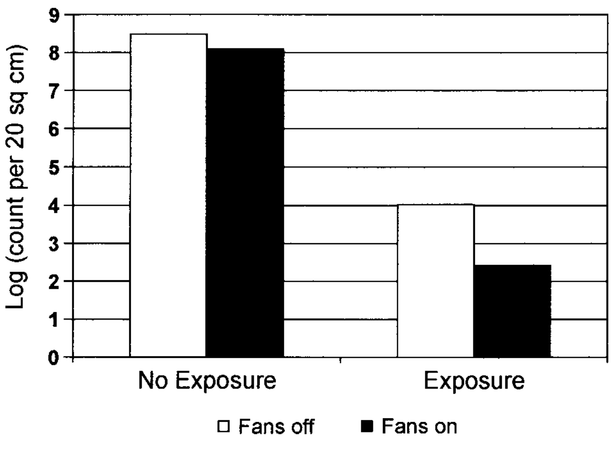


Fig. 2. Reduction in microbial counts on surfaces due to fogging with and without the use of a fan.

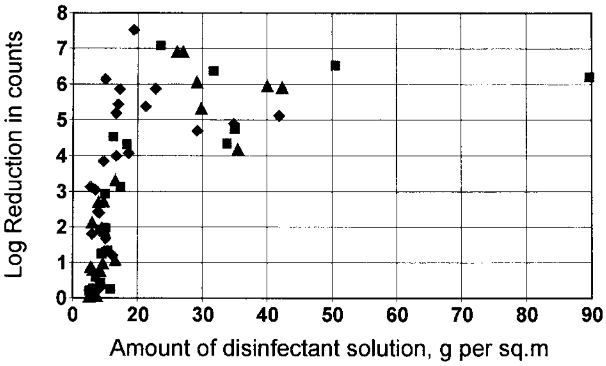


Fig. 3. Example of the relationship between reduction in microbial counts and the amount of disinfectant solution applied to a surface.

[8] measured organism counts ranging from 100 to 53,000/m^3 in three meat-processing factories at different stages of production. Similar values (1 to 15000 cfu/m^3) were measured by Ueda *et al.* [9] in a rice mill. Generally, airborne counts of a few hundred per m^3 are found in high-care food production environments, although counts are continually reducing as manufacturers aim to further improve hygiene and extend the shelf-life of the food.

Many food manufacturers use fogging in the belief that it reduces the numbers of airborne microorganisms. It is difficult to examine by experiment the mechanisms by which fogging has an effect on such organisms. Creating an aerosol of microorganisms for such an experiment imposes mechanical and physiological stresses on the organisms and these affect their recovery [10]. Straat *et al.* [11] also found that under certain conditions *Serratia marcescens* can metabolize and divide in aerosol droplets (in conditions of 95% relative humidity and 30°C). However, increases in bacterial numbers during fogging are unlikely due to short fogging times, generally less than 1 h. Reductions in airborne counts may also be found because the organisms have deposited rather than been killed in the air by the disinfectant.

Experiments have been carried out to measure the reduction in airborne counts during fogging. *S. aureus* or spores of *B. subtilis* var. *globigii* were used because these organisms are resistant to damage during aerosolization. The aerosol was created using the following procedure.

A suspension of the organisms was diluted to give approximately 10^7 organisms per millilitre. The solution was placed into a Collison nebulizer and aerosolized for 5 min to produce an airborne concentration of approximately 10^7 organisms per m^3 of air. The nebulizer uses compressed air to produce a high velocity jet which forms a low-pressure region above the liquid in the nebulizer causing the liquid to rise up through a tube and in to an airstream. This generates large droplets which then impact on a wall to produce small droplets which exit the device [12]. Air samples were taken using a Surface Air Sampler (SAS) (Cherwell Laboratories Ltd., 114 Churchill Road, Bicester, Oxon, UK) and a MicroBio (F.W. Parrett Ltd., 65 Riefield Road, London, UK). These air samplers draw in a known volume of air over a defined time period. In the tests on fogging this was 120 l over 90 s. Microorganisms in the sampled air impact onto an agar surface contained in a Rodac plate within the sampler. After sampling the Rodac plates were removed and incubated at 30°C for 48 h when the number of colonies on the plate were counted.

Fig. 4 shows an example of the reduction in airborne counts achieved by fogging a room (30 m^3) with a quarternary ammonium based disinfectant. In this example, the viable count in the air has shown a three-log reduction with the fogging treatment. The mechanism(s) causing this reduction is not known. The sizes of the fog droplets containing disinfectant and those containing organisms are very similar with respective volume median diameters measured using laser-based systems of 8 and 4 µm, respectively. Consequently, the relative velocity of the droplets will be very small, and the possibility of collision and coalescence is very small except near to the nozzle where the fog droplet velocity is very high. Another possibility is that the rapid changes in relative humidity of the air lead to the organisms becoming non-viable, a mechanism which is described by Cox [13]. To the food manufacturer, the mechanisms are not important; the reduction in airborne viable counts has been demonstrated.

Which chemical application systems should be used?

A variety of chemical application systems can be used for fogging disinfectants. The most commonly used units in large installations are systems using twin-fluid nozzles which are supplied with compressed air and disinfectant solution. A significant factor affecting the

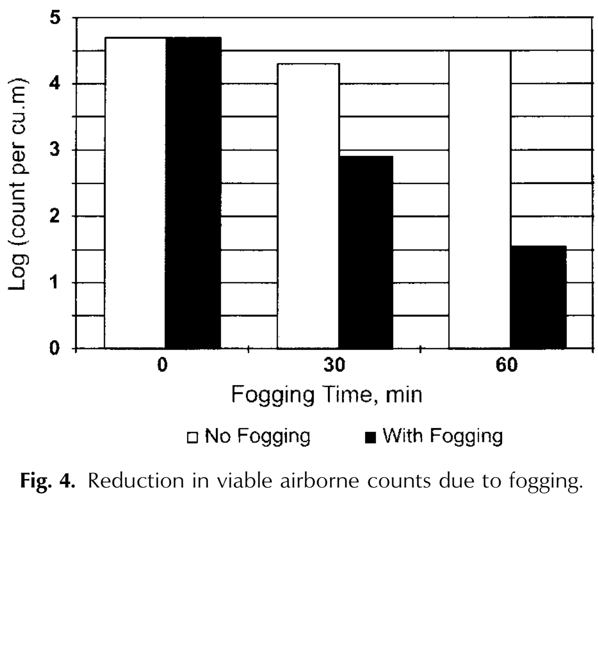


Fig. 4. Reduction in viable airborne counts due to fogging.

dispersal of the fog is the size of the droplets. It would seem reasonable to assume that large droplets will settle quickly and not disperse well whereas small droplets would remain airborne for longer periods and disperse easily. However, there is a need to define quantitatively the effect of particle size on flight time and dispersal. The use of numerical models to predict these variables is the most efficient approach.

Models of airborne dispersion of droplets

The physical mechanisms governing the dispersion of droplets in air are complicated. Models to predict dispersion are generally based on either a Eulerian or Lagrangian approach. The Eulerian approach treats the particulate phase as a continuum and describes particle concentration in time and space. Dispersion coefficients, analogous to diffusion coefficients in Fick's law, are required to predict the dispersion and this approach is valid over only a limited range of conditions [14,15]. The Lagrangian approach calculates the trajectories of individual particles; deposition occurs when particles reach a surface. This approach can account for turbulence structures [16] and inertia and trajectory crossing [17]. It has been applied to combustion [18] and spraying [19] and was used to model the fogging process.

The Lagrangian approach requires knowledge of the mean air flows and the instantaneous (turbulent) fluctuations. The mean velocities are predicted directly using a computational fluid dynamics (CFD) code which solves the continuity equations for mass and momentum with the ideal gas equation and a description of the turbulence [20]. Estimating the turbulent fluctuations is far more difficult. The turbulence model in the CFD code predicts the turbulent kinetic energy (k) and dissipation rate (ϵ). We need to determine the fluctuating velocities that will produce the same turbulent kinetic energy and dissipation rate as those predicted by the CFD code. Lagrangian stochastic models (also known as random flight models) are used to carry out this procedure. A large number of instantaneous velocity fields could produce the required values of k and ϵ, and it is necessary to use rigorous random flight models to ensure reliable predictions. Reynolds [21,22] and Reynolds *et al.* [23] describe the types of model and their uses.

The CFD code sub-divides the space to be considered (for example, a process area) into imaginary control volumes and the air velocity in each volume is calculated. Once the air velocity fields are known, droplet velocities can be calculated using Newton's second law:

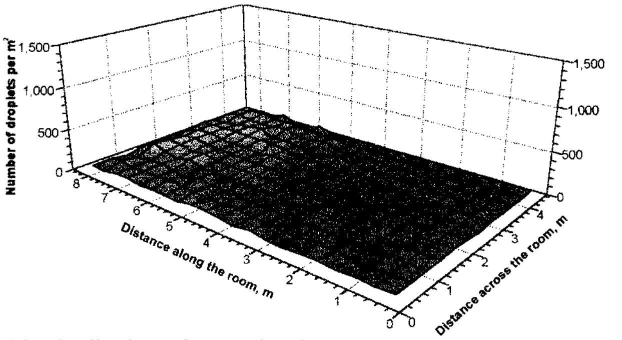
$$m(\mathrm{d}u/\mathrm{d}t) = F$$

where m and u are the mass and velocity of the droplet, t is time and F is the net force on the droplet, including drag, pressure gradient, buoyancy and added mass. This equation is applied to every droplet considered by the model in all control volumes throughout the fogging period. A typical fogging nozzle will produce around 10^{12} droplets each second so it is clearly impractical, based on computational requirements, to predict the movements of every droplet produced during a typical fogging period of 20 min. Instead, the particle size distribution is subdivided into ranges and the movements of a certain number (often tens of thousands) of droplets in that range are predicted. The calculated deposits are then scaled-up to ensure that the true particle size distribution and overall flow rate of chemical has been used.

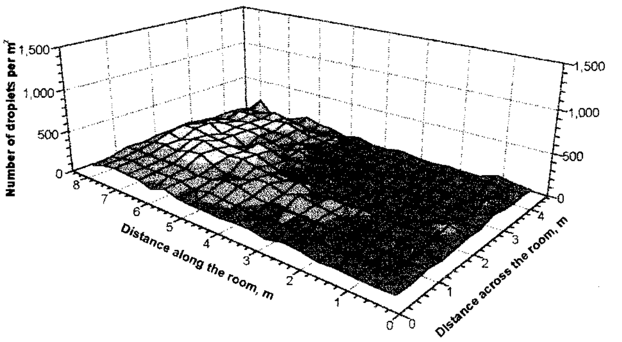
Definition of the best particle size

A fogging treatment will typically consist of a period of chemical supply through the nozzle followed by a period when the air and disinfectant supply have been stopped and the droplets are allowed to settle. (Sometimes the air supply may be maintained for a short period after the chemical has been stopped to clear the feed pipes. Also, the ventilation system may be used to clear the fog). During the period of chemical supply, typically 15–30 min, the air flow pattern within the room is developing and during the first 20 min of the resting period, which may be typically 45 min or longer, the flow is still transient. However, there are currently no rigorous random flight models capable of predictions of dispersion in transient flows. Furthermore the computational requirements for predicting transient flows in large rooms, such as processing environments in the food industry, are too great to enable the air flows to be predicted within a reasonable time. Consequently, predictions have been based on a steady flow field created by the flow from the nozzle. This will tend to over estimate the flight times of the airborne droplets.

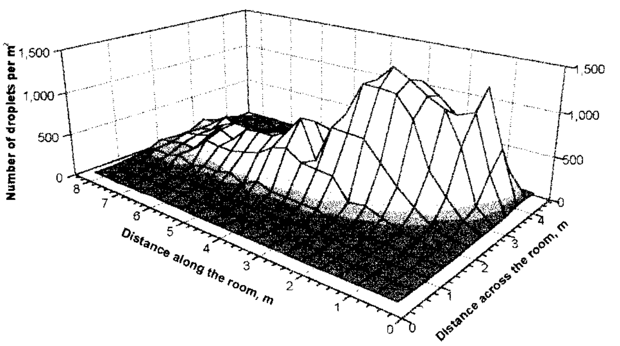
Fig. 5 shows the predictions of the deposits of 10,000 droplets of three different sizes on the floor of a room (8.55 m long by 4.7 m wide by 4.4 m high). The nozzle was located on the short wall at 2.67 m from one wall and 3.3 m from the floor. The smallest droplets (5 μm) disperse well and produce a uniform coverage on the floor. However, many of them remain airborne for several hours which would prevent operators from entering the room due to the risk of inhalation of the chemical. The 15 μm droplets produce a fairly uniform coverage and remain airborne for around 45 min, although this depends on the air flow in the room (both from the nozzle and any other sources such as ventilation systems, although these would normally be inoperative during fogging). The large 35 μm droplets do not disperse well, tending to deposit on to the floor close to the nozzle. The modelling studies suggested that a particle diameter of 15 μm would be most suitable for fogging as good dispersion was achieved and, provided that sufficient nozzles are used, application and settling times of 15 min and 45–60 min could be used.



(a) Distribution of 5 μm droplets



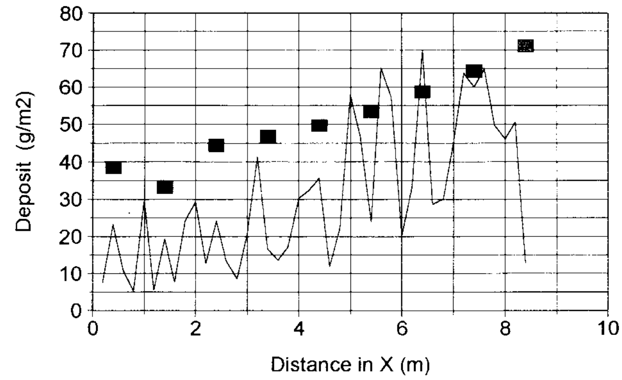
(b) Distribution of 15 μm droplets



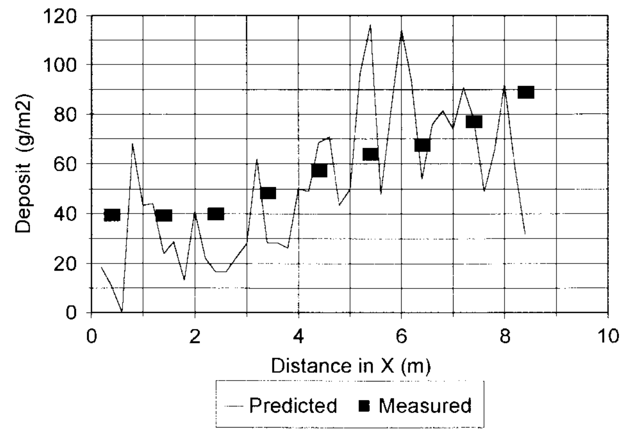
(c) Distribution of 35 μm droplets

Fig. 5. (a–c) Deposits of disinfectant droplets on the floor of a room showing the effects of droplet size on uniformity of coverage [24].

To verify the predictions from the model, experiments were carried out in a room with the layout described above. The particle size distribution produced by the nozzle was measured using a phase-Doppler analyser and the volume median diameter found to be 8 μm. Based on the particle size distribution and liquid flow rate, it was calculated that 9.6×10^{11} droplets were produced during each second of the application period (20 min). Since it is impractical to compute the tracks of so many droplets, the movements of only 1000 droplets of each size band were used (2 μm band widths over the full range of particle size). The deposits created by each of those 1000 particles of each size were then scaled-up in proportion to the measured particle size distribution. Fig. 6 shows the measured and predicted deposits on the floor along the centre-line of the nozzle and near to one of the walls. In both cases, the predicted data shown by the line is much more erratic than the smooth measured data. This is due to the relatively small number of tracks of droplet movements used in the simulations compared to the actual number of droplets deposited in the test. The model tends to predict the magnitude of the deposits and the gradual increase in deposits with distance along the room. However, near to the walls of the room, the model tends to underestimate the deposits of liquid. This suggests that, in the model, as the particles move towards a wall they continue on their path and deposit on the wall rather than moving with the air flow which goes towards the wall and then downwards towards the floor. The particles in the model have attached to the wall so they are no longer able to deposit on to the floor near to the wall consequently the model tends to under predict the deposits in these regions. Further work to improve the predictions in these regions and to investigate the influence of transient flows is being carried out.



(a) Deposits, 1 m from the wall



(b) Deposits, on centreline of the nozzle

Fig. 6. (a–b) Measured and predicted deposits of liquid after fogging. Deposits measured 1 m from one wall and along the centre-line of the nozzle.

Conclusions

Fogging is widely used in the chilled food industry. Its effectiveness on upward-facing surfaces has been demonstrated. Earlier work which found an insignificant effect probably used inadequate application devices which supplied insufficient chemical and possibly non-uniformly; twin-fluid applicators are recommended. Much of the deposition of the chemical is due to sedimentation which means that vertical surfaces and, in particular, upward-facing surfaces do not receive as much deposit as downward-facing surfaces. Using the nozzles to provide a spray, rather than fogging, action can lead to effectiveness on vertical and upward facing surfaces. A spray action can be achieved by locating the nozzle near to the target and directing the jet towards the target—this type of action may have led to the conclusion in some earlier studies that an adequate action of fogging can be achieved on vertical surfaces. The use of more aggressive disinfectants, such as peracetic acid or aldehyde based formulations, which produce a vapour action, can also lead to effectiveness on vertical surfaces.

Advanced computational models have been used to simulate the movements of airborne droplets of disinfectant. The models are generally adequate, except near to vertical surfaces, and were used to show that the optimum particle size lies in the range 10–20 μm which allows dispersion and settling in a time acceptable for cleaning regimes in the chilled food industry. Further research is needed to improve the models and to investigate techniques, such as electrostatic fogging, which can improve the coverage on to vertical and downward-facing surfaces.

A guidance booklet on the use of fogging in the food industry has been produced and is available from MAFF Food Technology Unit, 650 St Christopher House, Southwark Street, London SE1 0UD, UK.

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References

1 McRay, R.J., Dineen, P. and Kitzke, E.D. (1964) 'Disinfectant Fogging Techniques' in *Soap Chemistry Specialities* 40(75–78), 112–114

2 Darlow, H.M. (1969) 'Disinfection in Fermentation Laboratories' in *Process Biochem* 4, 15–16, 24

3 Edwards, L.D. (1978) 'A Major Approach to Infection Control?' in *Illinois Med. J.* 153, 121–124

4 Daschner, F., Frank, U. and Just, H.-M. (1987) 'Proven and Unproven Methods in Hospital Infection Control in Intensive Care Units' in *Chemioterapia* 6, 184–189

5 Hedrick, T.I. (1975) 'Engineering and Science of Aeromicrobiological Contamination Control in Dairy Plants' in *Chemistry and Industry* 20, 868–872

6 Holah, J.T., Rogers, S.J., Holder, J., Hall, K.E., Taylor, J. and Brown, K.L. (1995) 'The Evaluation of Air Disinfection Systems' in *CCFRA R&D Report No. 13*

7 Holah, J.T. (1995) 'Airborne Microorganism Levels in Food Processing Environments' in *CCFRA R&D Report No. 12*

8 Worfel, R.C., Sofos, J.N., Smith, G.C. and Schmidt, G.R. (1996) 'Airborne Bacterial Contamination in Beef Slaughtering Dressing Plants with Different Layouts' in *Dairy, Food and Environ. Sanitation* 16, 440–443

9 Ueda, S., Yamazaki, M., Machida, A., Akao, A. and Kuwabara, Y. (1988) 'The Ecological Study of *Bacillus cereus* in Rice Crop Processing (3). Airborne *B. cereus* in Rice Mills' in *J. Antibacterial Antifungal Agents* 16, 459–464

10 Andersen, J.D. and Cox, C.S. (1967) 'Microbial Survival' in *Airborne Microbes*, pp. 203–226 Cambridge University Press, Cambridge

11 Straat, P.A., Wolochow, H., Dimmick, R.L. and Chatigny, M.A. (1977) 'Evidence of Incorporation of Thymidine into Deoxyribonucleic Acid in Airborne Bacterial Cells' in *Appl. Environ. Microbiol.* 34, 292–296

12 Mitchell, J.P. (1995) 'Aerosol Generation for Instrument Calibration' in *Bioaerosols Handbook* (Cox, C.S. and Wathes, C.M., eds), pp. 101–175, Lewis Publishers, Boca Raton, Florida

13 Cox, C.S. (1995) 'Stability of Airborne Microbe and Allergens' in *Bioaerosols Handbook* (Cox, C.S. and Wathes, C.M., eds), pp. 77–79, Lewis Publishers, Boca Raton, Florida

14 Snyder, W.H. and Lumley, J.L. (1971) 'Some Measurements of Particle Velocity Auto-correlation Functions in Turbulent Flows' in *J. Fluid Mech.* 48, 41–71

15 Corrsin, S. (1974) 'Limitations of Gradient Transport Models in Random Walks and in Turbulence' in *Adv Geophys.* A18, 25–60

16 Zhou, Q. and Leschziner, M.A. (1981) 'A Lagrangian Particle Dispersion Model Based on a Time-Correlated Stochastic Approach', in *Am. Soc. Mech. Eng., Fluid Eng. Div., Gas–Solids Flows* 121, 255–260.

17 Etasse, E., Meneveau, C. and Poinsot, T. (1998) 'Simple Stochastic Models for Particle Dispersion Including Inertia, Trajectory Crossing, and Continuity Effects' in *Trans. Am. Soc. Mech. Eng.* 120, 186–192

18 Gosman, A.D. and Ioannides, E. (1981) 'Aspects of Computer Simulation of Liquid-fuelled Combustors' in *J. Energy* 7, 482–490

19 Shuen, J.S., Chen, L.D. and Faeth, G.M. (1983) 'Evaluation of a Stochastic Model of Particle Dispersion in a Turbulent Round Jet' in *Am. Inst. Chem. Eng. J.* 29, 167–170

20 Patankar, S.V. (1980) '*Numerical Heat Transfer and Fluid Flow*', Hemisphere Publishing Corporation, New York

21 Reynolds, A.M. (1997) 'A Lagrangian Stochastic Model for Particle Trajectories in non-Gaussian Turbulent Flows' in *Fluid Dynamics Res.* 19, 277–288

22 Reynolds, A.M. (1997) 'Modelling Particle Dispersion within a Ventilated Airspace' in *Fluid Dynamics Res.* 22, 139–152

23 Reynolds, A., Harral, B. and Burfoot, D. (1998) 'Predicting Particulate Dispersion for the Food Industry' in *Mathematics Today* 19–21 February.

24 Burfoot, D. (in press) 'The Importance of Air Flows in Design' In *Proceedings of European Experts Colloquium on Consumer Protection, Labour Safety and Hygiene, European Community, Brussels*