CFD MODELIZATION OF LEGIONELLA'S ATMOSPHERIC DISPERSION IN THE EXPLOSIVE OUTBREAK IN MURCIA

Antonio J. CONSUEGRO[1], Antonio S. KAISER[1], Blas ZAMORA[1], Antonio VIEDMA[1], Francisco SÁNCHEZ[1], Mónica HERNÁNDEZ[1], Manuel LUCAS[2], Javier RUIZ[2]

[1]Technical University of Cartagena, Spain
[2]Miguel Hernández University, Elche, Spain

Keywords: CFD, Legionella, outbreak, cooling tower, atmospheric dispersion, drift.

ABSTRACT: Cooling towers, among other equipments, could have an important atmospheric impact, becoming a source of pollutants or biological agents. The most important, due to its frequency and importance of the outbreaks, is Legionella. Since its discovery in 1976 in Philadelphia, where the total number of cases reached more than 200 of those more than 30 died, several outbreaks have been reported causing tens of deaths. The most important one due to its spread took place in the city of Murcia (Spain), in 2001, with more than 600 cases and where 23 out of 70 investigated cooling towers were positive to Legionella Pneumophila.

In the present work, a validated numerical modelization using the Computational Fluid Dynamics (CFD) code ANSYS Fluent is employed to simulate the dispersion of the drift from the cooling tower causative of the outbreak in the real urban environment of Murcia in the days of highest emissions, which are located by means of the number of infections given by the epidemic curve. The results of the modelization are compared with the results of the epidemiological investigation carried out by the Epidemiology Service at the Consejería de Sanidad de Murcia.

The main objective of this modelization is to predict a cooling tower influence area, what will help to reduce environmental and personal impact in case of an eventual infection of its water, or, as it is used in here, to improve the resources used to find the focus of infection after an outbreak has taken place.

The modelization was previously validated using data from an experimental cooling tower installation. The data set that was measured includes cooling tower parameters such as water and air flow, inlet and outlet water and air temperature, atmospheric conditions (by means of a meteorological tower and meteorological station) but also droplet diameter at the cooling tower outlet and droplet deposition in the surroundings using the water sensitive paper technique. Several cases were employed to validate the modelization, including a wide range of atmospheric conditions and cooling tower configurations.

1 INTRODUCTION

The most important risk of cooling towers is related to the atmospheric emission of droplets generated inside them. These droplets, known as drift, can be a vector for the dispersion of pollutants and infectious agents. Its outbreaks' frequency and the importance of its implications make the dispersion of Legionella the most important of the risks related to cooling towers. Controlling and predicting the characteristics of the dispersion of cooling towers drift can clearly be an important advantage to prevent outbreaks or, at least, to have a quicker response to them, which would result in lower numbers of infections and, surely, personal losses. CFD is presented to be an effective tool for this purpose.

1.1 *CFD prediction of atmospheric dispersion*

There are some analytical alternatives to solve the problem of atmospheric dispersion of particles in different environments. Although most of them are widely employed and have been sufficiently validated, they cannot be considered as the most adequate for the problem of urban dispersion of water droplets, where phenomena such as air humidity, condensation, evaporation, wind wakes around obstacles, etc., have to be taken into account. Droplet evaporation could be the most important phenomena to be accounted as it plays an important role on cooling tower drift dispersion (Consuegro et al. 2012). Some of the most known analytical models are the 'Industrial Source Complex, ISCST3, the 'Seasonal/Annual cooling Tower Impact (SACTI) Model' or the 'PAL2.1' model. Although some of them include cooling tower plume analytical models, they do not include accurate modeling of the phenomena previously stated, which have much to say about water droplet dispersion. In addition to analytical models, experimental models, such as wind tunnel, could provide reasonably good results. However, the need of scaling geometric and physical magnitudes by means of physical similarity and dimensional analysis results in too low velocities for this particular problem, as a direct consequence of the small diameter of droplets, which may lead to results distortion (Petersen 2004).

Numerical simulation by CFD can accurately reproduce the influence of buildings and more complex obstacles in the atmospheric dispersion of particles and also include effects of droplet evaporation or atmospheric stability. Thus, CFD is presented as the best promising tool to solve atmospheric dispersion of water droplets given the fact that it can take into account almost everyone of the physical phenomena related to it. In (Meroney 2006) measured data of cooling tower drift is compared with the results obtained from a CFD simulation of a 3D plain domain, without obstacles. A protocol to correct atmospheric dispersion of cooling tower drift in urban environment is suggested in (Meroney 2008) where different seasonal periods and meteorological conditions are included. The protocol is also proved in a complex 3D urban model. In (Lucas et al. 2010) the ambient psychometric conditions influence on the deposition of cooling tower drift employing a CFD modeling similar to that employed in (Meroney 2006) is established. Another noteworthy work on this field is (Blocken 2006[1] and 2006[2]) where wind and rain impact on building facades are numerically characterized.

2 THE EXPLOSIVE LEGIONELLA'S OUTBREAK IN MURCIA

The explosive Legionella's outbreak took place in the city of Murcia during the first days of the summer of 2001. The outbreak was detected on July 7 and 449 cases of infection were confirmed until July 22. Taking into account the sensitivity of the test employed to confirm the presence of Legionella in the patients' urine and historical data of pneumonia hospital admissions, the Epidemiology Service of the Region of Murcia estimate the total number of infections between 636 and 696 (García et al. 2003). Six deaths were confirmed, which means a lethality of around 1%.

The study of the epidemic curve and the legionellosis incubation period suggests that the maximum emission took place between June 29 and July 1. During those days very high temperatures were measured in the city of Murcia, as well as very low velocity winds and thermal inversion episodes. Furthermore, the city of Murcia is geographically placed in a pre-coastal lagoon in the Segura River valley, flanked by mountain chains in the south and west, with a wet micro-weather and with trend to urban emissions accumulation without the presence of strong winds that disperse them (Gutiérrez et al. 2002). As Legionella infection is usually contracted via inhalation of aerosolized water - some authors also suggest aspiration (Yu 1993, Murder et al. 1986, Woo et al. 1992) - the accumulation of emissions on urban environments are very dangerous. In addition, high temperature is determinant for the development of the bacteria. Therefore, the geographic conditions of the city of Murcia and the atmospheric conditions on those days play an important role in the occurrence of the Legionella's episode.

The case-control study made by the Epidemiology Service resulted in the identification of a cooling tower from a city center hospital as the source of the outbreak. This case-control study was based on an epidemiologic questionnaire where data like place of residence or recent mobility around the city was asked. The information collected from the infected people included their itineraries around the city, the means of transportation employed, their frequency and also if they have gone through 30 specific areas of the city, where potential sources of contaminated aerosols were placed. The analysis of the exposition areas was made in two ways after collecting the information from the case-control study. The first way of analysis was based on the fact that the infected went through or not by the block around a risky installation. The second way was based on the fact that the infected went through or not the area of a 200 meter radius circle around an installation (Fig.1). By means of this two-ways analysis, eight high risk areas were studied. At this point, CFD is thought to be a very useful tool, as the analysis of exposition areas could be more accurate if the potential scope of the drift of each risky installation is previously defined.

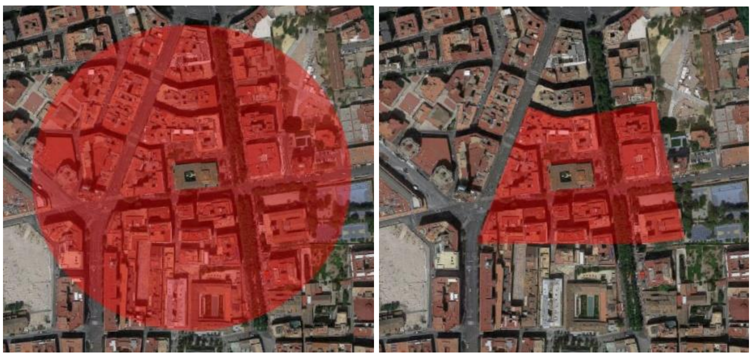

Figure 1: Methods of analysis of the exposition areas. Left: 200 m radius circle around building. Right: block around building.

Among a total number of 45 installations classified as "high risk", 29 were cooling towers. Other 28 installations analyzed were classified as "medium risk" and 53 as "low risk".

The multivariate analysis applied to the information collected by the case-control study showed significant association of the area around the city center hospital with the illness. Later, the microbiological study of the water samples collected from a cooling tower of the hospital identified two colonies of Legionella Pontiac Philadelphia as indistinguishable from those obtained from patients.

1.2 *Subsequent cooling tower installations barriers*

After this explosive outbreak, the cooling tower source of it was replaced by a less efficient air-cooling system. In 2003, two years after the outbreak, the Spanish government published a very restrictive law to prevent and control legionellosis (Ministerio de Sanidad y Consumo 2003). Furthermore, local and regional governments published more restrictive ordinances than that of the Spanish government in the subsequent years (BORM 2011). The many laws published after the explosive outbreak of the city of Murcia are strong barriers to the installation of new cooling towers and also to the operation of the existing ones.

A strictly updated maintenance of cooling towers and the application of new designs of cooling tower parts which make them more efficient and reduce the atmospheric emission of droplets (Zamora et al. 2012), in addition to more accurate predictions of scopes of cooling towers drift would result in a less restrictive framework for this installations and in a more efficient cooling system, with a lower energy consumption and lower carbon dioxide emissions.

3 METHODS

This study is the real application of an intensive experimental validation of a 3D urban modelization made by the Fluid Dynamics Research Group of the Technical University of Cartagena. The CFD numerical modelization was developed to obtain accurate predictions of drift and deposition of droplets in urban environments (Consuegro et al. 2014). The experimentally validated modelization is now applied to a 3D simplified urban simulation of the environment of the surroundings of the cooling tower source of the outbreak, in the city center of Murcia, Spain.

The software employed is ANSYS Fluent, a commercial finite volume general purpose code that solves fluid flows by dividing the geometric model of the environment into a large number of smaller volumes and by solving the discretized Reynolds Averaged Navier-Stokes (RANS) equations on those volumes. For the reproduction of the atmospheric boundary layer (ABL) (the layer of the atmosphere closest to the ground, where mixing effects, heat transfer and momentum exchange take place between the air and the Earth surface) the k-ε turbulence model is also employed. Finally, water droplets are treated as particles which transfer mass and momentum with the surrounding air by an Eulerian-Lagrangian model. Although inherent characteristics of the problem studied suggest a transient study, its magnitude makes it impossible with nowadays computer capabilities. Thus, a stationary simulation of a time period is run, using averaged values of each parameter involved.

The geometric model of the urban environment is composed by two different meshes: an inner cylinder and an outer hexahedron. By this, any wind direction can be simulated with a simple rotation of the inner part of the mesh, avoiding new mesh generation and also the problems related to inlet velocities in directions non perpendicular to the inlet surface. The inner cylinder has a radius of 280 m and includes the buildings around the cooling tower together with the hospital where the cooling tower is located. The hospital is placed in the center of the domain. It has three different roof levels and the cooling tower is located on the highest one, 29 m from the ground. The outer hexahedron has a dimension of 800 x 800 x 400 m (Fig. 2). The structured staggered mesh has a total number of cells around 3.5 million, whose averaged length is between 5-6 m. These geometric characteristics of the mesh generated are also the result of the previously validated modelization.

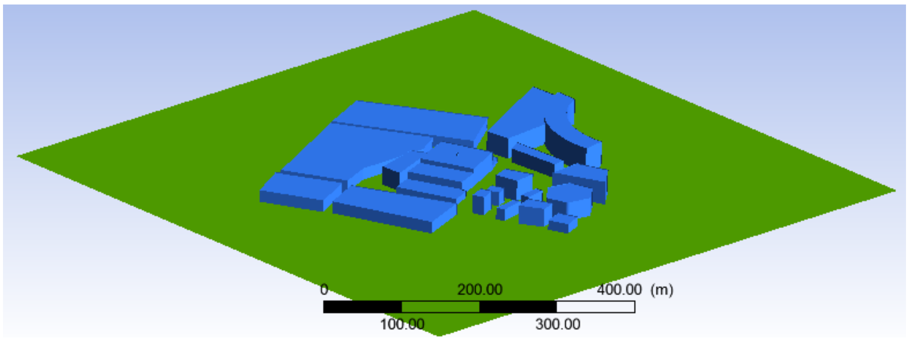

Figure 2: Details of the computational 3D urban domain of the city center of Murcia.

3.1 *Boundary conditions*

In order to guarantee the goodness of the numerical simulations it is necessary to impose a set of appropriate boundary conditions which also has to be close to the reality of the urban environment. Vertical profiles of temperature and humidity were obtained from annual averages of the measurements made by the State Meteorological Agency in the city of Murcia in years previous to the outbreak. Wind velocity and turbulence parameters are provided by the k-ε model approach of Richards and Hoxey where they develop vertical profiles of wind velocity, turbulent kinetic energy and turbulent dissipation rate - Eq. (1-3)- which are solution of the system equations (Richards 1993).

$$u(z) = \frac{u^*_{ABL}}{\kappa} ln\left(\frac{z+z_0}{z_0}\right) \quad (1)$$

$$k = \frac{(u^*_{ABL})^2}{\sqrt{C_\mu}} \quad (2)$$

$$\varepsilon = \frac{(u^*_{ABL})^3}{\kappa(z+z_0)} \quad (3)$$

where u^*_{ABL} is the ABL friction velocity, κ is the von Karman constant (0.41), C_μ is a constant of the turbulence model (0.9), z is the height and z_0 is the roughness height, which is set to 1, as recommended by U.S. EPA for the considered environment.

The rest of the boundary conditions were selected from the previous validated modelization (Consuegro et al. 2014) as the conditions to correctly reproduce the ABL achieving horizontal homogeneity, i.e., avoiding possible variations in the vertical profiles of atmospheric magnitudes as they travel through the computational domain. These conditions are *outflow* for the outlet surface of the domain, *symmetry* for the lateral surfaces, *rough wall* for the bottom of the domain and *sliding wall* for the top boundary fixing its velocity as the wind velocity at that height. Temperature values at the top and bottom of the domain are also imposed in their respective boundary conditions. This set of boundary conditions is adjusted using the measurements made by the State Meteorological Agency during the days of maximum emission of the outbreak. These measurements include hourly averages of wind velocity, wind direction, temperature and relative humidity (Fig. 3).

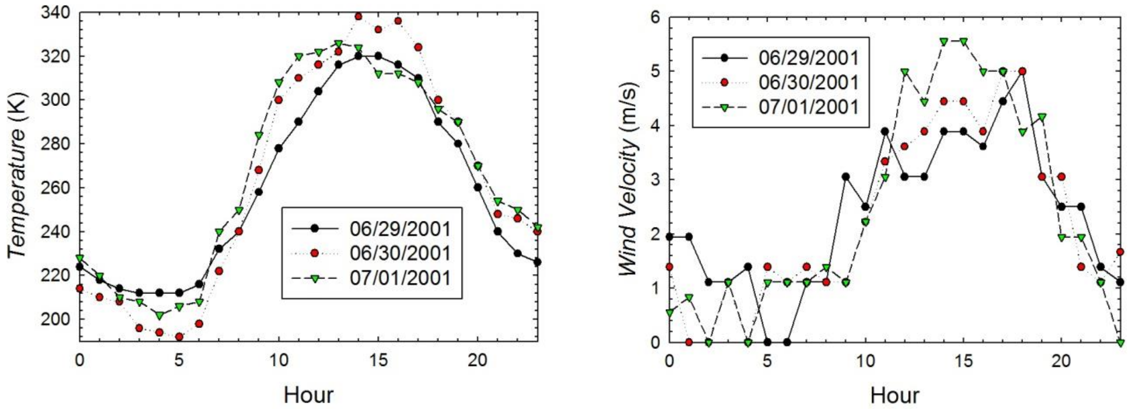

Figure 3: *Left* - Temperature evolution measured in the city of Murcia during the maximum emission days of the Legionella's outbreak. *Right* - Hourly averaged wind speed measured in the city of Murcia during the maximum emission days of the Legionella's outbreak

Averaged conditions measured at the end of the afternoon of June 29 are employed for the simulation. That is a time with high levels of pedestrian traffic and the atmospheric conditions would have result in one of the lower levels of evaporation among the maximum emission days. The results of this simulation are also compared with those of a simulation using the averaged conditions from the daytime of July 1. Nevertheless, for a complete mapping of the cooling tower influence area, all the possible wind directions must be simulated. In atmospheric studies, it is common to employ twelve wind directions as representatives of the entire circumference.

3.2 *Experimental validation of the modelization*

A real cooling tower installation was employed for the experimental validation of the numerical modelization. This cooling tower is located on the roof of a building in the Miguel Hernández University of Elche. The cooling tower is equipped with the necessary instruments to monitor its working parameters such as water and air temperature, water flow, power consumption and air flow. The characteristics of the air at the outlet of the cooling tower are boundary conditions employed for the simulations. That air includes water droplets, which are modeled by a Rosin-Rammler diameter distribution adjusted by the measurements made by the water sensitive paper technique (Ruiz et al. 2013). This technique consists of obtaining the characteristics of the droplets inside an air flow placing yellow papers through that flow which turn blue with the contact of water. Applying correction factors it is possible to obtain very accurate data of droplet diameters. The water sensitive paper technique is employed for the characterization of the flow that exits the tower but it is also one of the most important tools to validate drift and deposition of droplets by placing papers on the cooling tower surroundings to obtain the characteristics of the deposition and compare them with simulation results.

The atmospheric variables employed for the adjustment of the boundary conditions of the simulation and also for the validation of its results were measured by means of two different equipments. The first one is a weather station placed near the cooling tower, at the same height of its outlet. This station continuously acquires data of wind velocity and direction, temperature and relative humidity. The second equipment is a meteorological tower build up in the south of the building were the experimental cooling tower is installed. The tower has three anemometers and three weather vanes to measure module and direction of wind speed, three hygrometers for humidity measurements, three thermometers to measure air temperature and one pressure sensor. Wind speed, temperature and humidity sensors are placed at three different heights from the ground: 15 m, 25 m and 40 m; the barometer is located at the height of the experimental cooling tower, i.e., 10 m. The instrumentation is calibrated following the North American National Institute of Standard and Technology (NIST) models and the experimental data measured is treated following the U.S. Environmental Protection Agency (EPA) recommendations.

Around 20 experimental cases were made in different ambient conditions and a variety of cooling tower configurations. Numerical results of atmospheric conditions were compared to those obtained from measurements, showing great concordance. As previously stated, the most important source of validation is the deposition of droplets on the surroundings of the cooling tower. The weight of the water deposited and the diameter distribution of the deposited droplets measured by the water sensitive paper technique were compared with numerical results, obtaining good agreement in most of the cases. Changing atmospheric conditions are pointed out as the cause of discrepancies between numerical and experimental results. The way to avoid this is by the segmentation of the simulation in several ones, where more stable atmospheric conditions could be obtained. Segmentation was also tested showing great results, achieving a great improvement when many simulations are employed instead of just one.

4 RESULTS

The analysis of results shows accurate reproductions of vertical profiles of the involved magnitudes along the entire computational domain (Fig. 4). Temperature profiles are very stable along the domain, which is a very important requirement as evaporation has a crucial role. Vertical profiles of wind velocity are also very homogeneous along the domain. As expected, the presence of buildings has an important effect on wind velocity near the ground, obtaining lower velocities in that region inside the urban area than in the outer part of the domain, where no buildings are modeled.

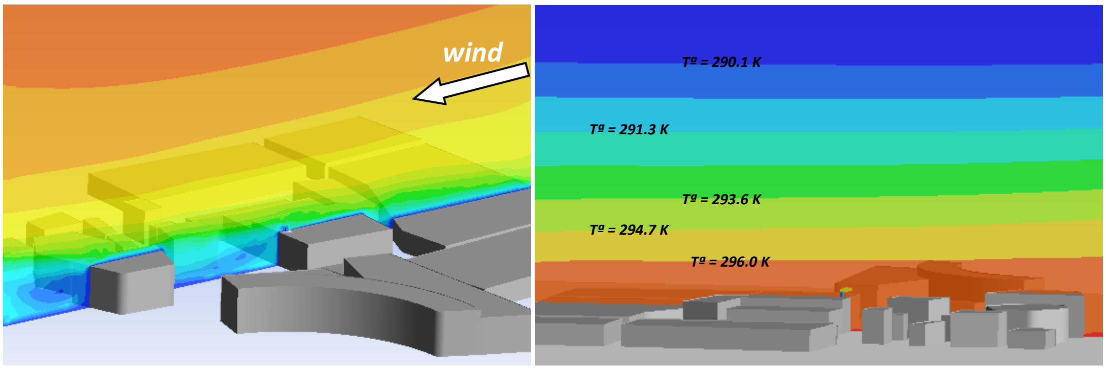

Figure 4: Contours of wind velocity magnitude (*left*) [0-5 m/s] and temperature (*right*).

Vertical profiles measured by the State Meteorological Agency at 12:00 Z during the maximum emission days (June 29-30 and July 1) show that the temperature evolution with height in the lower part of the atmosphere (around 0.02 ºC/m) is above the limit for neutral atmosphere (0.00981 ºC/m). This means high atmospheric dispersion as there is a strong mixing effect in the atmosphere layers. Nevertheless, the particular conditions of those days (high temperatures and low humidity levels) make the influence of atmospheric stability indiscernible, being the most significant effects horizontal dispersion and evaporation.

The horizontal dispersion of droplets reaches a maximum length of 140 m from the cooling tower exit (Fig. 5) although the flow patterns at pedestrian levels in the building environment result in big dispersion angles, covering a great lateral area. Previous experimental experiences and CFD simulations show that the temperature and humidity levels observed for this case result in evaporation levels that prevent droplets from reaching farther distances. Dispersion above 150 m is only obtained for lower temperature and humidity levels, like those observed in winter or autumn.

Around 47 % of the droplets evaporate before reaching any surface or zone where a person could inhale them and get infected while 53 % of them reach the ground or a building facade. Flow patterns around buildings have an effect of lateral dispersion of cooling tower drift, reaching bigger areas, not always in the direction of higher strata wind. For the simulation using the averaged values of daytime of July 1, 68 % of the droplets evaporate but almost all the rest impact on the hospital terrace or on the facades of the building near it in the downstream direction. Thus, wind direction and atmospheric conditions are key parameters for the resulting dispersion of drift in complex urban environments, since the presence of an obstacle downstream could make no droplet to reach the ground and high levels of temperature and humidity could result in strong evaporation of droplets.

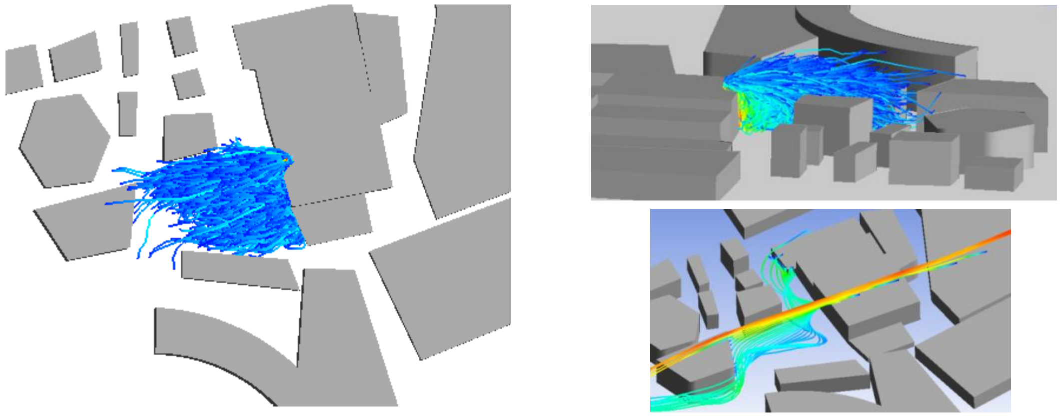

Figure 5: (*Left, top-right*) Droplet tracks from two different views. (*Bottom-right*) Streamlines in the drift deposition zone.

Fig. 6 shows droplet diameter distributions at the cooling tower exit and at the ground for the simulation of July 29. The Y-axis expresses the mass fraction of droplets with a diameter greater than that specified in the X-axis. Both ranges of diameters follow a Rosin-Rammler distribution but one can see the important effects of evaporation since most droplets at the ground are smaller than the droplets at the cooling tower exit, being the distribution of droplets at the ground more concentrated in lower diameters. For instance, 32 % of the mass fraction at the cooling tower exit is composed by droplets with a diameter above 400 μm while less than 10 % of the mass fraction at the ground are droplets of such diameters.

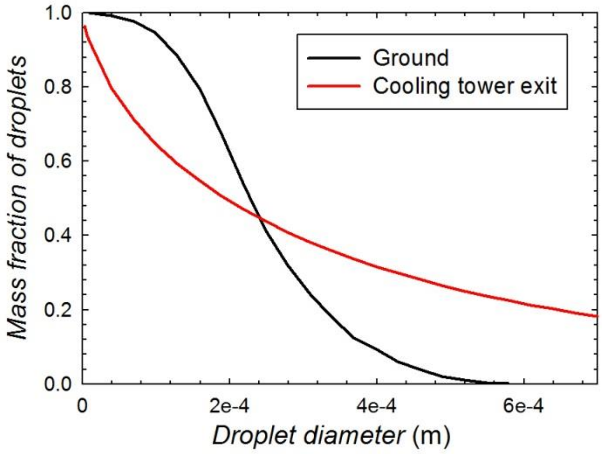

Figure 6: Droplet diameter distributions at the cooling tower exit and at the ground expressed following the Rosin-Rammler distribution (Y-axis is the mass fraction of droplets with a diameter greater than X).

5 CONCLUSIONS

In this study, a previously experimentally validated modelization of the atmospheric dispersion and deposition of cooling tower drift is applied to simulate the real conditions of the explosive Legionaries' disease outbreak in the city of Murcia during the summer of 2001. The modelization gives geometrical characteristics, meshing parameters, mathematical models (physical, turbulence, discretization…) and boundary conditions to be adjusted to any other urban environment with its particular atmospheric conditions, ensuring that the results obtained will be in good agreement with reality.

The results of the modelization of the outbreak show that droplet dispersion patterns are in agreement with an explosive outbreak, as most of the drift emitted by the cooling tower reaches pedestrian areas and the size distribution of those droplets is big enough to contain the bacteria. In addition, the case-control study developed to find the source of the outbreak could have been reduced, taking into account only one of the methods of analysis of the exposition areas: the block around a risky installation. It is unlikely that droplets could reach 200 m from any installation during those days, so that, this method of analysis could have been rejected. Wind levels and the high evaporation, result of high temperature and low humidity, make droplets travel distances below 150 m before its disappearance. Nevertheless, as stated before, a more complex study should be made, including any wind direction measured during the days of the outbreak, in order to have a more detailed description of the cooling tower influence area.

This CFD modelization could be applied to any other cooling tower environment to predict dispersion and deposition of drift, reducing and limiting the area to study in a hypothetical infection. This would result in lower response time of the sanitary technicians and in faster localization of outbreak sources, which definitely means less infections and personal losses.

ACKNOWLEDGEMENTS

This research is founded by the Research Projects ENE2007-68106-CO2-02, ENE2010-21679-C02-01 of the National Plan of R+D (Ministerio de Ciencia e Innovación, Spain).

REFERENCES

Blocken B, Carmeliet J 2006[1]. The influence of the wind-blocking effect by a building on its wind-driven rain exposure. *Journal of Wind Engineering and Industrial Aerodynamics,* 94:101-127.

Blocken B, Carmeliet J 2006[2]. On the validity of the cosine projection in wind-driven rain calculations on buildings. *Building and Environment,* 41:1182-1189.

BORM (Boletín Oficial de la Región de Murcia) nº 255 2011. Final approval of the modification of the Atmosphere Protection Ordinance. 41273-41295.

Consuegro A J, Kaiser A S, Zamora B, Sánchez F, Lucas M, Hernández M 2014. Numerical modeling of the drift and deposition of droplets emitted by mechanical cooling towers on buildings and its experimental validation. *Building and Environment*, 78:53-67.

Consuegro A J, Kaiser A S, Zamora B, Ruiz J, Lucas M 2012. Numerical analysis and experimental validation of the influence of buildings environment in the dispersion of cooling tower drift in different ambient conditions. *Proc. of The Second International Conference on Building Energy and Environment (COBEE2012),* Denver, CO, USA, August 1-4 2012.

García-Fulgueiras A, Navarro C, Fenoll D 2003. Legionnaires' disease outbreak in Murcia, Spain. *Emerg Infect Dis*. 9:915-21.

Gutiérrez Molina C, López Casares R, Gómez Campoy E 2002. Outbreak of Legionella's disease in Murcia, at July 2001. The environmental point of view. *Revista Salud Ambiental*. 2(1): 22-31.

Kröger D G 2004.*Air-cooled heat exchangers and cooling towers*, Volume I. Tulsa, Okla.: PennWell.

Lucas M, Martinez P J, Ruiz J, Kaiser A S, Viedma A 2010. On the influence of psychometric ambient conditions on cooling tower drift deposition. *International Journal of Heat and Mass Transfer*, 53:594-604.

Meroney R 2006. CFD prediction of cooling tower drift. *Journal of Wind Engineering and Industrial Aerodynamics*, 94:463-490.

Meroney R 2008. Protocol for CFD prediction of cooling-tower drift in an urban environment. *Journal of Wind Engineering and Industrial Aerodynamics,* 96:1789-1804.

Ministerio de Sanidad y Consumo 2003. Real Decreto 865/2003, July 4, by which hygienic-sanitary criteria for the prevention and control of legionellosis are established.

Petersen R L 2004. ISC3 and PRIME versus wind tunnel observations for a power plant with hyperbolic cooling towers. *13[t] Conference on the Applications of Air Pollution Meteorology.* Vancouver, BC, Aug. 23-26 2004.

Richards P J, Hoxey R P 1993. Appropriate boundary conditions for computational wind engineering models using the k-e turbulence model. *Journal of Wind Engineering and Industrial Aerodynamics*, 46-47:145-153.

Ruiz J, Kaiser A S, Ballesta M, Gil A, Lucas M 2013. Experimental measurement of cooling tower emissions using image processing of sensitive papers. *Atmospheric Environment*, 69:170-181.

Zamora B, Kaiser A S 2012. Simulación numérica del flujo turbulento de aire con gotas de agua dispersas a través de separadores de torres de refrigeración. *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería.* 28(3):148-160.