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# Simulation and Experimental measurement of Clean in Place nozzle using PDA

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Clean In Place, Nozzle, PDA, CFD, VOF

## Zusammenfassung

Selection and optimization of a Clean In Place (CIP) system is a complex process. The CIP nozzles used in the system plays a huge role in the efficiency of the entire system. Therefore, numerical investigations are widely employed by many industrial processes, especially in the hygiene critical industries, such as Food, Beverage and Pharmaceutical industries. An enormous quantities of cleaning agent and water are consumed on a daily basis during their cleaning processes. Hence finding a reliable and efficient design and operating condition of the cleaning nozzle based on understanding the internal and external flow properties and their optimization is a priority for these companies.

This paper presents the comparison between experimental measurement and the numerical prediction of the flow features and spray characteristics of a currently available flat fan nozzle which is widely used for the industrial cleaning in place application. The flow features are measured experimentally using the optical measurement technique, Phase Doppler Anemomerty (PDA) system which is then compared numerically. Computations of the CIP nozzle system were conducted using a finite volume based commercial computational fluid dynamics (CFD) solver, StarCCM+ V12.04. The numerical and experimental results are further compared and presented.

## Einleitung

Cleaning in place system is one of the continuous processes that most of the food and beverage industries are using these days. As the name suggests here the cleaning can be done without dismantling the system equipment. There are two ways of performing the CIP process. Either the cleaning detergents are put to drain immediately after they have been used, which is called as single use cleaning. Whereas in recovery CIP, where the cleaning have to be done for less dirty objects, like tanks and pipes that have cold surfaces, the cleaning solution is not that dirty after one cleaning cycle and it is reused. In single use the cleaning solution is always fresh when cleaning is started and the equipment needed to perform single use CIP is rather inexpensive. On the other hand, this way of CIP system has a high running cost and high environmental load. In recovery type CIP, less cleaning detergent will be consumed, and less water and energy leading to reduced environmental load. But the equipment needed to recover the cleaning solutions is highly expensive compared to the single use cleaning.

Cleaning in place is a major process in guaranteeing food safety in food processing plants. Carrying out cleaning in place effectively and efficiently is important as it contributes an overall low total cost of ownership. Every cleaning time is a downtime, which means the equipment is not productive. Cleaning must also be carried out safely, because very strong chemicals are involved that can be harmful to people and to equipment. Finally, it should be carried out with the least impact on the environment by using minimal amounts of water and detergents and by maximizing the re-use of resources [1].

Soil or dirt is held on the surfaces by adhesive forces. To get the soil to leave a surface the forces that hold the impurity on the surface have to be overcome. There are four parameters that make up cleaning: Mechanical force, thermal force (heat), chemical force and the time the forces act.

**Figure 1. Clean in Place System [1]**

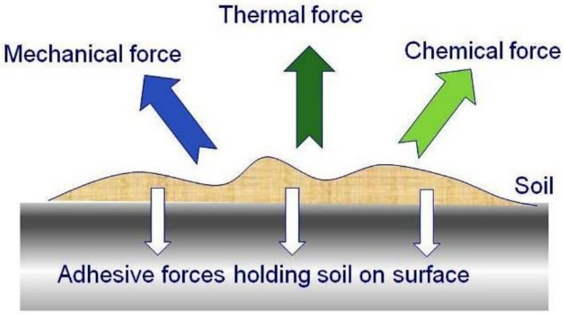


**Figure 2. Forces acting on soil [1]**

Energy is required in a cleaning process in order to remove the soil and once dissolved, keep it in solution and carry it away. The energy required is kinetic, chemical and thermal energy. These three factors, together with the contact time determine the effectiveness of the cleaning. These four parameters are interconnected and depend on each other, which means that if any of the parameters is changed, the other three might need to be adapted so as to give the same end result as before. They are usually grouped in a diagram called **Sinner's circle** and include flow, temperature, concentration and time.

In this paper we are only considering the mechanical force in the cleaning in place which is the shear forces created by the flow. In general the CIP system is said to have flows that are turbulent and that the flow velocity should be at least 1.5 m/s to have an adequate mechanical force [1]. This can be achieved by using a nozzle. A nozzle restricts the area through which the water flows, which in turn increases the velocity of the water flow and thereby increases the impact at which the water jet hits the surface. For hygiene critical industries, it is important to have the maximum mechanical forces. Hence the nozzle selection is a key parameter in CIP system for its efficiency. Selection of the nozzle is based on different technical features like: Nozzle efficiency, droplet size, spray angle, impact force, spray distribution etc.

The nozzle efficiency can be defined as the ratio between the energy available at the nozzle inlet and outlet. The energy is used to increase the liquid speed and create the spray, the difference being the energy lost during the process because of friction. The droplet size depends on the structure of the atomizer, intensity of the liquids energy, liquid surface tension and density. The size of the atomized droplets is not uniform and hence the average droplet size, Sauter mean diameter (SMD) becomes an important factor. The spray angle is the angle formed by the cone of the liquid leaving a nozzle orifice. The spray angle and the distance between the nozzle orifice and the target surface to be covered determine the spray coverage. The force generated by the jet of water deflected by the impact surface is the impact force. The uniformity of a jet impact force and distribution influence the washing effect. Based on the application different nozzles are used which has different spray distribution patterns, like full cone, hollow cone, flat spray, spoon flat fan, straight jet etc. Figure 3 shows the different kinds of spray pattern.

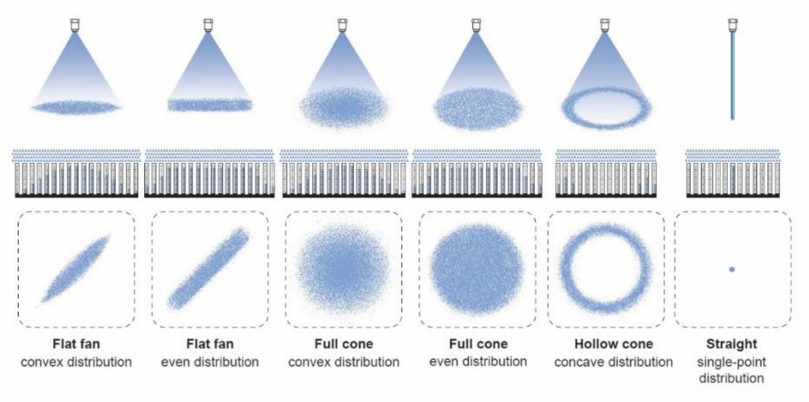


**Figure 3. Types of Spray pattern and its distribution [2]**

In this paper we are discussing about the flat fan nozzle, which is widely used in the cleaning in place industry and due to its simplified design. It has wide flat and relatively coarse spray pattern with uniform distribution.

## Measurement Techniques

In order to measure the droplet size and the particle velocity there are number of techniques available including optical and mechanical methods. Optical methods are normally used these days due to its non-intrusive techniques where the droplets size and velocity can be measured without interfering with flow.
In this work Phase Doppler Anemometry (**PDA**) method has been used to measure the droplet size and the multiple components of velocity. PDA is a point measurement technique where we can measure the droplet size and velocity simultaneously. The underlying theory for the measurement is based on light scattering interferometry and the Doppler Effect. Measurements are made in the volume of the intersection of two focused laser beams and are conducted on single particles as they move through the sample volume. Particles scatter light from both laser beams and generate an optical interference pattern. The frequency of the pulsation of light intensity is proportional to the velocity of the particle. Each detector is mounted at different angles and converts the optical signal into a Doppler burst. The phase shift between the Doppler signals from 2 different detectors is a direct measure of the particle diameter. In this paper we are discussing only about the velocity measurement from the PDA, since we are comparing them with the numerical simulation.

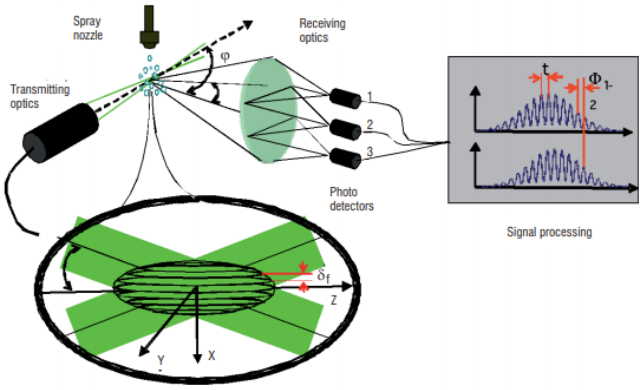


**Figure 4. Principle of PDA [2]**

## CFD Simulation Setup

Numerical Simulation is widely employed by many industrial processes, especially in the hygiene critical industries, such as Food, Beverage and Pharmaceutical industries. In this study we are investigating the flow features and spray characteristics of a currently available flat fan nozzle which are widely used in industrial cleaning in place application. The droplet velocity at the axial position is measured using the PDA system. These measurement results are used to validate the external multiphase simulations and thereby as an initial step towards the design optimization. By doing so, the reliability of the currently used numerical methods and the commercial codes can also be verified. The external multiphase simulation is carried out using different numerical solvers and the best suitable and efficient one is presented in this paper. Based on these studies further optimization will be carried out with the help of some genetic algorithms or neural network algorithms.

The spray simulations are considered as multiphase flows, where multiple fluids coexist in the flow domain. Here the phases are mixed at macroscopic level, where the phases are not chemically related. For modelling multiphase flows there are two different approaches: Eulerian-Eulerian and Eulerian-Lagrangian approach. In Eulerian-Eulerian approach, the observer considers the particles, bubbles or droplets to be a continuum passing through a fixed volume. Whereas in the later one the observer tracks parcels of particles as they move through space and time. The Eulerian multiphase model considers there to be a primary continuous phase in which bubbles, droplets or granules of a secondary phase are dispersed. The conservation equations for mass, momentum, energy and turbulence are solved for each phase. Hence called Eulerian- Eulerian model. This model covers full range of volume fraction for each phase. In this paper the simulation was carried out using finite volume code StarCCM+, where the volume of fluid method. Volume of fluid method is a one fluid approach where the simple multiphase advection model keeps tracking the interface between the phases by tracking the distribution of each phase. This model considers a single effective fluid whose properties vary according to the volume fraction of individual fluids.

$$\alpha_i = \frac{V_i}{V}$$

The mass conservation equation for fluid i reads:

$$\frac{\partial(\alpha_i \rho_i)}{\partial t} + \nabla.(\alpha_i \rho_i v) = \rho_i S_{\alpha_i}$$

It can be rearranged into an equation in integral form and can be used to compute the transport of volume fraction $\alpha_i$. The mass conservation equation for the effective fluid is obtained by summing up all the component equations and using the condition $\sum_i \alpha_i = 1$.
In this paper the simulation of flat fan nozzle is compared with the experimental measurement. The CAD geometry of the nozzle is as shown below along with the simulation domain.

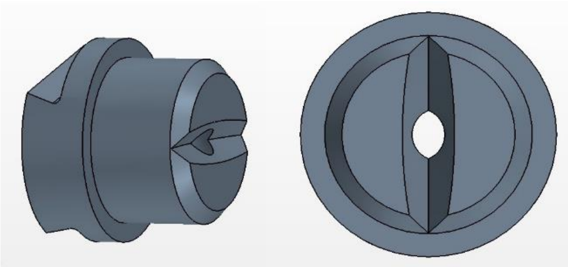


**Figure 5. CAD geometry of the flat fan nozzle**

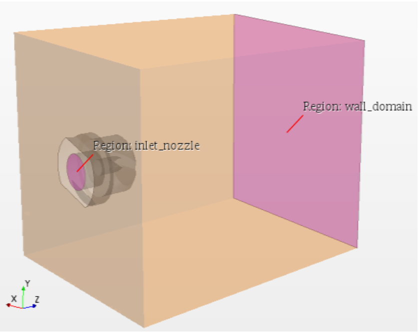


**Figure 6. Simulation domain**

The meshing was carried out with the trimmer cell meshing method, which generates a structured mesh for the computation domain with local refinements to resolve the boundary layers as well. The wall at which the water hits is placed at different axial distance. A sample of the mesh is shown below.

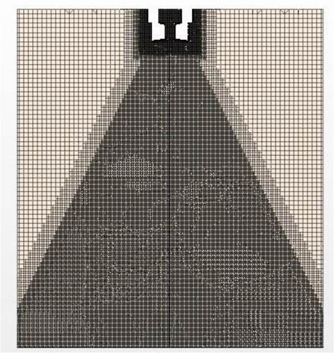


**Figure 7. Structured mesh with local refinement**

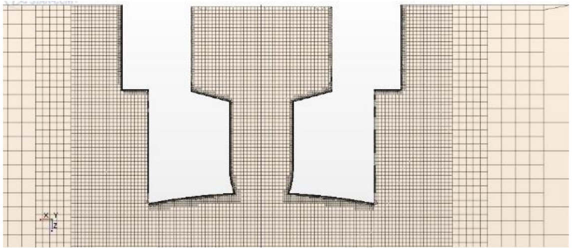


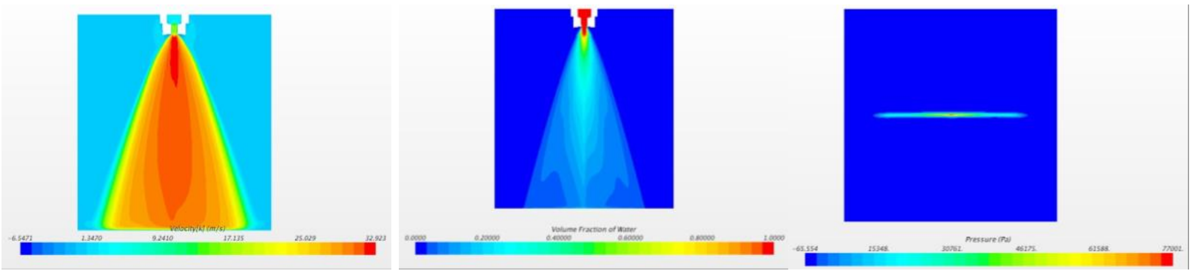
**Figure 8. Boundary layer mesh resolution**

Prism layers are used in order to resolve the boundary layers and wall treatment approach was considered in order to limit the computational demands. The first layer thickness was close enough to the walls to yield y+ value of 5. With a base size of 1.5mm, for 100mm domain distance the mesh resolution was about 10 million cell elements.

At inlet the mass flow boundary condition was imposed for respective operating pressure based on the experimental value. Rest all the surfaces are given as pressure outlet boundary except the wall where the water jet hits. The inlet is initialized with volume fraction of water as primary phase and rest everywhere as air. Implicit unsteady computations were carried out with adaptive time stepping with CFL number limited to 5. For unsteady RANS computations K- Epsilon turbulence model was used to close the equations. Two layer shear driven wall treatment and second order up-wind convection term is used. The surface tension force, interface momentum dissipation and gravity is activated. All the computations were run in HPC system with 40 processors for a physical time of 2 seconds and keeping in mind the convergence.

## Results

Here the results are shown for the velocity distribution along the center plane of the nozzle domain and the pressure at the wall plane where the jet hits for three different wall distances. This can be directly related to the impact measurement, which in turn describes about the cleaning effectiveness. The velocity contour, volume fraction of water and the wall pressure for three different wall distances are shown below.



a b c

**Figure 9. Contour plots for 6bar operating pressure for a wall distance of 100mm**
**a. Velocity contour b. Volume Fraction of water c. Wall Pressure**

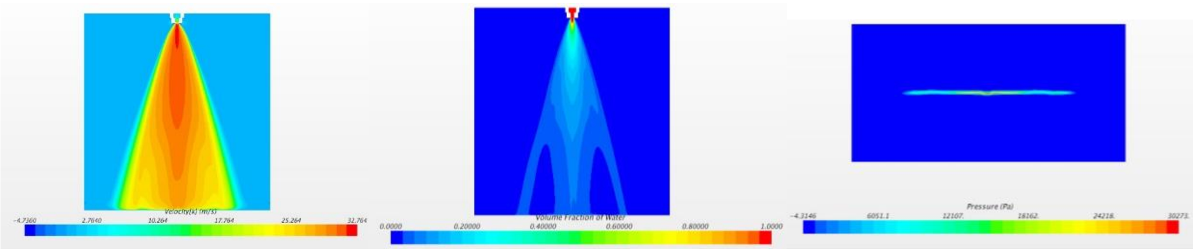


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**Figure 10. Contour plots for 6bar operating pressure for a wall distance of 200mm**
**a. Velocity contour b. Volume Fraction of water c. Wall Pressure**

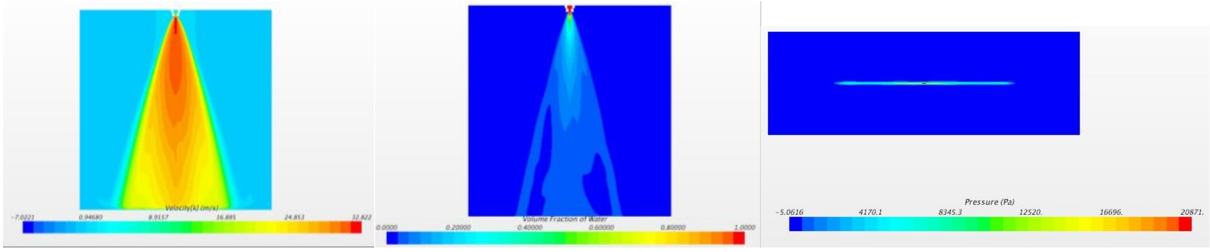

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**Figure 11. Contour plots for 6bar operating pressure for a wall distance of 300mm**
**a. Velocity contour b. Volume Fraction of water c. Wall Pressure**

From the above shown results its clear that the area covered by the water jet increases as the distance between the nozzle exit and the wall increases. Similarly the spray angle also widens and the impact pressure decreases as the wall distance increases. This describes the impact force relation as well. The direct comparison for force on the wall for varying operating pressure and the axial velocity at different position for a constant operating pressure and varying operating pressure which is compared with the experimental values.

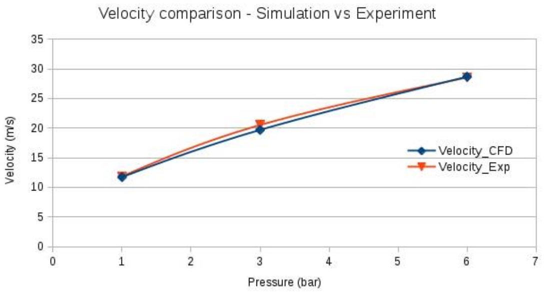

**Figure 12. Velocity comparison at 100mm for different operating pressure**

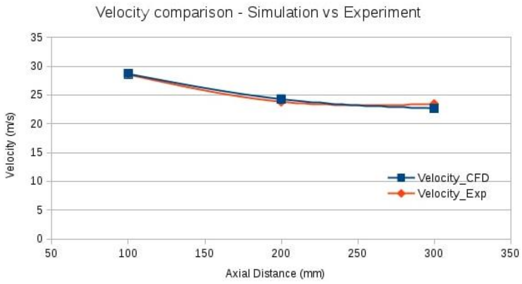

**Figure 13. Velocity comparison at 6bar at different axial position**

The graphs above show the comparison between numerical and experimental measurements of axial velocity for different operating pressure keeping the wall distance constant and velocity comparison for different axial position keeping the operating pressure constant. These two graphs have good agreement between the experimental and numerical measurements. The force on the wall for different operating pressure shows a linear relationship in the numerical simulation as well.

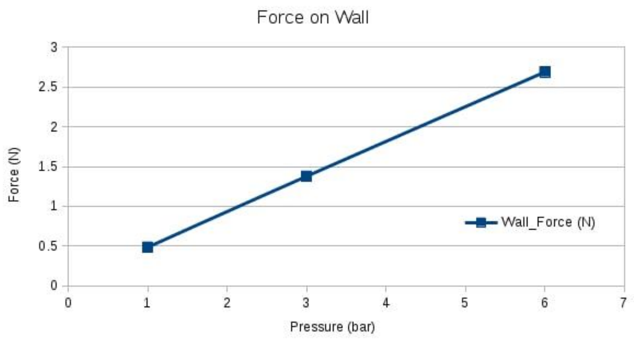

**Figure 14. Force on the wall for different operating Pressure**

Based on these data it is evident that further optimization can be done with the help of the volume of fluid method approach using numerical simulations. And these data can be used for further optimizing the nozzle on a virtual engineering framework and minimizing the computational effort.

## Conclusion

In order to investigate the velocity field in the spray generated in the flat fan nozzle, PDA measurements were performed for different working regimes and the PDA measurements were made at 3 different distance from the nozzle exit where the atomization was expected to be complete all droplets are spherical and also for 3 different operating pressures by keeping the wall distance constant. The experimental results were also compared with the numerical simulation of the flat nozzle and it shows a good agreement. This shows the ability of using numerical simulation with less computational effort to generate sufficient data to train the algorithm for further optimizing the nozzle using some optimization algorithm, which is considered as the extension of the project.

## Literature

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