Spray Simulations to Support the Development of a Monte Carlo-Based Spray Cooling Model

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Spray cooling is a crucial method for meeting today’s thermal management challenges in many areas including space applications, high speed computers, microelectronic components and other high energy density devices. The extreme complexity of the flow created by the impact of millions of droplets per second creates a need for a heat transfer model which incorporates enough physical detail to yield accurate predictions while being sufficiently simplified to use in routine design computations. The spray cooling group at West Virginia University (WVU) is pursuing a coordinated program of computational simulations and laboratory experiments to develop a Monte Carlo-based spray cooling model that will satisfy this requirement. This paper reports our initial simulations of sprays. A companion paper focuses on progress in the laboratory. The results reported here include simulations of sprays generated by a pressure swirl nozzle and a full cone nozzle and their impact on surfaces. The goals of these simulations are to demonstrate that they can accurately reproduce the characteristics of sprays seen in previous numerical simulations and laboratory experiments and also to develop the capability to perform the simulations that will be needed in the development of the Monte Carlo spray cooling model. The computations have been performed using the commercial ANSYS FLUENT CFD software. The fully three dimensional and axisymmetric simulations use the Finite Volume Method (FVM) computational technique to solve the Navier-Stokes and continuity equations for the air and the Discrete Phase Model (DPM) to calculate the trajectories of discrete droplets. Sprays are injected using the pressure-swirl atomizer and full cone nozzle models which are sub-models of DPM in FLUENT. Inertial, gravity, viscous, and surface tension forces are accounted for but heat transfer has not yet been included.

Nomenclature

\[ h = \text{the distance from nozzle tip to impact surface (nozzle-to-surface distance)} \]
\[ \theta = \text{spray half angle} \]
\[ H = \text{cylindrical computational domain height} \]
\[ D = \text{cylindrical computational domain diameter} \]
\[ Re = \text{Reynolds number} \]
\[ g = \text{Gravity} \]
\[ P = \text{spray nozzle pressure} \]
\[ m = \text{total spray mass} \]
\[ m_s = \text{total mass of the spray liquid film that accumulates on the surface} \]
\[ M = \text{spray nozzle mass flow rate} \]

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I. Introduction

The interaction of sprays with wet and dry surfaces is the key feature in many engineering applications such as spray cooling and fuel injection systems\(^1\). Spray cooling with phase change offers the means to achieve the highest rates of heat transfer from microelectronic components and other high energy density devices, but the extreme complexity of the flow created by the impact of millions of droplets each second challenges the limits of human understanding. There is a need for an accurate predictive model based on sound physics that is sufficiently simple to be used for routine design calculations. Kuhlman and his students\(^2\)\(^-\)\(^4\) have proposed a Monte Carlo model to satisfy this need. Although the initial results have been promising, the Monte Carlo model relies on correlations that at present are based on inadequate data or unsubstantiated assumptions. The WVU spray cooling group is pursuing a coordinated program of computational fluid dynamics (CFD) simulations and laboratory experiments to develop the accurate correlations needed to establish the Monte Carlo-based spray cooling model as a reliable design tool. This paper reports the initial simulations of sprays and demonstrates their synergistic interplay with laboratory measurements. This combined approach assures that the simulations remain physically realistic while providing results over a much wider range of parameters than could be obtained in the lab (e.g. variable gravity).

The interaction between spray drops and a surface may involve inertial, surface tension, viscous, and gravitational forces. The geometric parameters and spray system schematic are illustrated in Figure 1. Figure 2 shows an actual spray image obtained from a full cone nozzle system using a high speed camera\(^5\). Figure 3 shows the basic parameters that affect the spray impact and cooling efficiency. Each of these basic parameters has a significant effect on the spray flow, impact dynamics and heat transfer. In this paper, fully three dimensional (3D) and two dimensional (2D) axisymmetric simulations of a hollow cone sprays are compared to justify the use of the axisymmetric model. Next, 2D axisymmetric simulations are presented in which gravity (g), spray flow rate (M), liquid viscosity (\(\mu\)), liquid density (\(\rho\)), liquid surface tension (\(\sigma\)), the distance from the nozzle tip to the impact surface (h), and the spray half angle (\(\theta\)) are varied in a full cone spray. These simulations do not include heat transfer.

A. Numerical Methods

The simulations reported here have been performed using the commercial CFD code ANSYS FLUENT Version 14.5 on a desktop computer. The Discrete Phase Model (DPM) of FLUENT has been used by many authors to model particles in variety of flow conditions including the calculations of rain drop trajectories around a car windshield\(^7\) and snow flake trajectories around snowplow trucks\(^8\). DPM has also been used to model spray particle trajectories, particle diameter distributions, and heat transfer\(^7\)\(^,\)\(^8\). In this study, the Discrete Phase Model (DPM) is implemented to model sprays in a full three dimensional (3D) cylindrical domain shown in Figure 1 and a two dimensional (2D) axisymmetric domain using the Finite Volume Method (FVM).

B. Numerical Setup

The computational domains are drawn in the Design Modeler (DM) section of ANSYS Workbench, and then they are transferred to the Meshing section to generate computational cells. After the solid and fluid zones are designed in DM, meshing and assignment of boundary conditions is completed in the Meshing module. The top surface of the cylindrical domain is defined as a constant pressure outlet while wall boundary conditions are applied at the side and bottom (spray impact) surfaces in the 3D domain.
The Discrete Phase Model (DPM) is a Lagrangian-Eulerian based modeling method, and it includes two different phases. The continuum phase (e.g. air) is phase 1 and it has a high volume fraction in a spray compared to phase 2. Phase 2 is the discrete phase, and it contains a number of particles (e.g. spray drops). Considering the high velocity of sprays after being injected from a nozzle, a $k$-$\varepsilon$ turbulence model is implemented to account for the turbulence effects. The surrounding gas is air at atmospheric pressure and room temperature (25°C). The spray liquid is water at room temperature.

The spray is generated using the FLUENT pressure-swirl atomizer model which is based on the Linearized Instability Sheet Atomization (LISA) model of Schmidt et al.\textsuperscript{9}. The Kelvin-Helmholtz and Rayleigh-Taylor (KHRT) model is used as the secondary drop break-up model. This model combines two different criteria based on the effects of Kelvin-Helmholtz waves caused by the aerodynamic forces and Rayleigh-Taylor instabilities caused by the acceleration of the shed drops ejected from the liquid sheet\textsuperscript{10}.

Two different fully 3D spray simulation cases and two exactly identical 2D axisymmetric cases using the pressure swirl nozzle that generates hollow cone sprays at isothermal conditions are presented in this paper in order to determine if the 2D axisymmetric model is sufficiently accurate. Subsequently, different spray parameters are investigated using the 2D axisymmetric full cone nozzle which represents the actual spray nozzle that is used in experiments. The parameters of the 3D cases are shown in Table 1. As seen in Table 1, the only changing parameters for these two cases are the distance from nozzle tip to the impact surface ($h$) and the spray half angle ($\theta$).

![3D computational domain, domain specifications, boundary conditions and spray half angle ($\theta$).](image1.png)

![A high speed video image that shows a spray injected from a full cone nozzle.](image2.png)

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Figure 3. Basic parameters that affect the spray impact and cooling efficiency.

### Table 1. Parameters of the full 3D spray simulations.

<table>
<thead>
<tr>
<th>Case</th>
<th>Gravity (m/s²)</th>
<th>Spray Liquid</th>
<th>Nozzle Pressure, P (Pa)</th>
<th>Mass Flow Rate, M (kg/s)</th>
<th>Nozzle-to-Surface, h (mm)</th>
<th>Spray Half Angle, θ (°)</th>
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</thead>
<tbody>
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<td>0.003</td>
<td>35</td>
<td>18</td>
</tr>
</tbody>
</table>

### III. Results

**A. Full 3D Spray Simulations**

Results for the two cases specified in Table 1 are presented in Figures 4-11 for simulation times between 0-7.5 ms. Figures 4 and 5 show the results of the spray formation, spray impact, the formation of splashing drops, and drop accumulation on the surface for Case 1 and Case 2, respectively. The three cartesian velocity components of spray drops for Case 1 and Case 2 are shown in Figure 6. Figure 6 indicates that the velocity of the spray drops in the x and y direction is axisymmetric between -27 m/s and +27 m/s for both Cases. Maximum x and y velocity in negative and positive direction (-27, +27 m/s) occurs for the spray drops that have accumulated on the surface (Fig. 6). Maximum spray velocity before the initial spray impact is 29.45 m/s in the negative z direction for Case 1 and 28.65 m/s in the negative z direction for Case 2 (Fig. 6). The splashed drops have a positive z velocity for both Case 1 (0-3.5 m/s) and Case 2 (0-5 m/s) as seen in Figure 6. This indicates that the splashed drops move upward with an angle based on the initial impingement angle. These results are consistent with the actual experimental results³. Figure 7 displays the spatial distribution of drop diameters at 5 ms. Figure 8 shows the time variation of the Sauter mean drop diameter \(d_{12}\) and the arithmetic mean drop diameter \(d_{10}\). Even though the Sauter mean drop diameters are very close, the maximum drop diameters are around 208 µm for Case 1 and 334 µm for Case 2. The Sauter mean drop diameters become smaller with time for both cases after the initial spray impact at around \(t = 1.5\) ms, and each of the cases follows the same curve which is shown in Figure 8. This is an expected result which is caused by the splashing mechanisms. Because of the impact of spray drops on the surface, the number of drops increases and they become smaller. The drop Reynolds number \(Re\) range for Case 1 and Case 2 is shown in Figure 9. The maximum Reynolds numbers are 423 for Case 1 (Fig. 9,a) and 573 for Case 2 (Fig. 9,b), and these results are consistent with the maximum drop diameters.
Figure 4. Spray injection, spray impact and liquid film formation on the surface for Case 1 ($h = 40$ mm, $\theta = 10^\circ$). (Particles are colored by the velocity magnitude-dark blue refers to lower velocity range (0-3 m/s) and red refers to higher velocity range (26-29.7 m/s), and time ($t$) in ms)
Figure 5. Spray injection, spray impact and liquid film formation on the surface for Case 2 ($h = 35$ mm, $\theta = 18^\circ$). (Particles are colored by the velocity magnitude-dark blue refers to lower velocity range (0-3 m/s) and red refers to higher velocity range (26-29.7 m/s), and time (t) in ms)
Figure 6. Three component velocity (m/s) distribution of spray drops for Case 1 \((h = 40 \text{ mm}, \theta = 10^\circ)\) and Case 2 \((h = 35 \text{ mm}, \theta = 18^\circ)\) at 5 ms. (Note that red refers to the positive direction and dark blue refers to the negative direction for each velocity components)
Figure 7. Spray drops diameter distribution (m) at 5 ms (a) Case 1 ($h = 40$ mm, $\theta = 10^\circ$) (b) Case 2 ($h = 35$ mm, $\theta = 18^\circ$). (Note that for (a) red refers to 188-208 $\mu$m, yellow refers to 126-146 $\mu$m, green refers to 84-105 $\mu$m, and dark blue refers to less than 22 $\mu$m; for (b) red refers to 301-334 $\mu$m, yellow refers to 201-234 $\mu$m, green refers to 134-168 $\mu$m, and dark blue refers to less 35 $\mu$m)

Figure 8. (a) The Sauter mean drop diameter ($d_{32}$) (b) the arithmetic mean drop diameter ($d_{10}$) with respect to time, $t$ (ms) for Case 1 ($h = 40$ mm, $\theta = 10^\circ$) and Case 2 ($h = 35$ mm, $\theta = 18^\circ$).

Figure 9. Reynolds number ($Re = \rho Vd/\mu$) of spray drops at 5 ms (a) Case 1 ($h = 40$ mm, $\theta = 10^\circ$) (b) Case 2 ($h = 35$ mm, $\theta = 18^\circ$).
The thickness of the liquid film that has accumulated on the impact surface at $t = 5$ ms is shown for both cases in Figure 10. The maximum thickness of 2.27 μm is at the center of the spray and the film thickness declines monotonically with radius for Case 1. The liquid film is more complex for Case 2 with a dimple near the centerline and an off center maximum of 1.62 μm.

![Figure 10. Flooded contours of the liquid film height at 5 ms for (a) Case 1 ($h = 40$ mm, $\theta = 10^\circ$) (b) Case 2 ($h = 35$ mm, $\theta = 18^\circ$). (Note that Red refers to 1.35-1.5 μm, yellow refers to 0.9-1.05 μm, green refers to 0.6-0.75 μm, and dark blue refers to less than 0.15 μm. Uncolored zones at the center region refers to the thickness more than 1.5 μm which include the maximum thickness: 2.27 μm for Case 1 and 1.62 μm for Case 2) ](image)

The variation of the total liquid film mass ($m_s$) that has accumulated on the impact surface is shown in Figure 11.a. Spray drops start to accumulate on the surface after around 1.5 ms which is the time when the first spray drops impinge onto the surface. The accumulated spray liquid film mass on the impact surface for Case 2 is more than Case 1 between the initial impact time (1.5 ms) and 4.2 ms (Fig. 11.a). However, the mass of spray liquid film for Case 1 becomes more than Case 2 between 4.2 ms and the simulation end time (7.5 ms).

Issa\textsuperscript{11} defined the spray impact efficiency ($\eta$) as the ratio of the mass flow rate of the spray liquid film that accumulates on the impact surface ($M_s = m_s / t$) to the mass flow rate of the spray nozzle ($M = m / t$) which is: $\eta = M_s / M$. Figure 11.b shows the spray impact efficiency ($\eta$) comparison of Case 1 and Case 2. Figure 11.b initially shows a similar trend with the spray liquid film mass ($m_s$) comparison shown in Figure 11.a. After the initial spray drops impinge onto the surface, the spray impact efficiency increases for both Case 1 and Case 2. However, the efficiency is higher for Case 2 compared to Case 1 until 4.2 ms. The efficiency of Case 1 remains almost constant after 4.5 ms whereas the efficiency of Case 2 starts to decrease until 6 ms and then increases again until the simulation end time which is 7.5 ms (Fig. 11.b). A higher number of splashed spray droplets at 4.5 ms and 6 ms can be clearly seen in Figure 4 and Figure 5 for Case 1 and Case 2, respectively. The decrease of the efficiency for Case 2 and the constant efficiency for Case 1 after 4.5 ms can be due to the higher number of splashed drops since these splashed drops are not included in the liquid film that has accumulated on the surface at that corresponding time (4.5-7.5 ms).

The spray liquid film mass on the surface is an important parameter for spray cooling. The spray impact efficiency can be helpful for understanding the spray cooling mechanisms since the total spray liquid film mass on the surface increases with an increase on the spray impact efficiency which can also increase the heat transfer between the liquid film and the heated surface.

![Figure 11.a. Spray drops start to accumulate on the surface after around 1.5 ms which is the time when the first spray drops impinge onto the surface. The accumulated spray liquid film mass on the impact surface for Case 2 is more than Case 1 between the initial impact time (1.5 ms) and 4.2 ms (Fig. 11.a). However, the mass of spray liquid film for Case 1 becomes more than Case 2 between 4.2 ms and the simulation end time (7.5 ms). ](image)

![Figure 11.b. Figure 11.b shows the spray impact efficiency ($\eta$) comparison of Case 1 and Case 2. Figure 11.b initially shows a similar trend with the spray liquid film mass ($m_s$) comparison shown in Figure 11.a. After the initial spray drops impinge onto the surface, the spray impact efficiency increases for both Case 1 and Case 2. However, the efficiency is higher for Case 2 compared to Case 1 until 4.2 ms. The efficiency of Case 1 remains almost constant after 4.5 ms whereas the efficiency of Case 2 starts to decrease until 6 ms and then increases again until the simulation end time which is 7.5 ms (Fig. 11.b). A higher number of splashed spray droplets at 4.5 ms and 6 ms can be clearly seen in Figure 4 and Figure 5 for Case 1 and Case 2, respectively. The decrease of the efficiency for Case 2 and the constant efficiency for Case 1 after 4.5 ms can be due to the higher number of splashed drops since these splashed drops are not included in the liquid film that has accumulated on the surface at that corresponding time (4.5-7.5 ms). ](image)
Figure 11. (a) Variation of the total liquid film mass, \( m_s \) (mg), on the surface with respect to time, \( t \) (ms) (b) Variation of the spray impact efficiency, \( \eta \) (%) = \( M_s / M \), with respect to time, \( t \) (ms) for Case 1 (\( h = 40 \) mm, \( \theta = 10^\circ \)) and Case 2 (\( h = 35 \) mm, \( \theta = 18^\circ \)). (Note that \( t = 0 \) ms is the time when spray is injected, \( t \sim 1.5 \) ms is the time when spray drops start to impinge and accumulate on the surface, and simulation end time is 7.5 ms)

B. Comparison of Full 3D and 2D Axisymmetric Spray Simulations

Full 3D spray simulations are computationally very expensive. It took several months of computation on a quad core desktop PC to get a fully converged solution for a single full 3D spray simulation for a limited spraying time (7.5 ms as reported in this paper). Therefore, it would be impractical to perform full 3D simulations to analyze different parameters effects on sprays. For this reason, the two full 3D spray cases (Case 1 and Case 2) described in the previous section are compared to two identical 2D axisymmetric spray simulations based on spray characteristics and spray impact efficiency.

For Case 1, the average drop diameters \( d_{32} \) and \( d_{10} \) are very close as shown in Figures 12.a and 12.b, respectively. The accumulated spray liquid film mass on the impact surface of Case 1 for full 3D and 2D axisymmetric sprays are very close until \( t = 6 \) ms (Fig. 13.a). After \( t = 6 \) ms, the spray liquid film mass is higher for the 2D axisymmetric spray. This can be explained due to the number of total splashing drops. The full 3D spray generates more splashing drops with time after spray impact on the surface. Since the liquid film mass on the surface does not include these splashing drops, more liquid film mass is obtained from 2D axisymmetric spray since it results in less drop splashing. Figure 13.b shows the comparison of the spray impact efficiency for full the 3D and the 2D axisymmetric Case 1 spray. Similar to the liquid film mass comparison shown in Figure 13.a, the spray impact efficiency is very close at the initial time but after \( t = 6 \) ms the 2D axisymmetric simulation results in higher spray impact efficiency which can be explained due to more spray liquid film accumulation on the impact surface, as a result of the reduced drop splashing.

Figure 12. Comparison of the average drop diameters (a) \( d_{32} \) (b) \( d_{10} \) for Case 1 (\( h = 40 \) mm, \( \theta = 10^\circ \)).
Figures 13. Comparison of Case 1 \((h = 40\ \text{mm}, \ \theta = 10^\circ)\) (a) the liquid film mass \((m_s)\) and (b) the spray impact efficiency, \(\eta\ (%)\).

Figures 14 and 15 show the drop velocity distributions for Case 1 for full 3D and 2D axisymmetric hollow cone spray simulations. Initial impact time is at \(t = 1.5\ \text{ms}\) for both 3D and 2D axisymmetric sprays. Spray liquid film formation on the impact surface is also very similar. However, there are some differences on the number of splashing drops. There are more splashing drops in the full 3D spray compared to the 2D axisymmetric spray (Fig. 14 and Fig. 15). The comparisons of the full 3D and 2D axisymmetric simulations for Case 2 are not included here but were similar to those of Case 1.

It is observed from the full 3D hollow cone spray simulations that the three component velocity distribution of spray drops for Case 1 and Case 2 (Fig. 6), and the distribution of drop diameters (Fig. 7.a for Case 1 and Fig. 7.b for Case 2) are symmetric about the centerline. It is concluded based on the comparisons between Case 1 and Case 2 simulations that sprays can be adequately simulated using a 2D axisymmetric model instead of full 3D since the spray characteristics such as the average drop diameters, average drop velocity distribution, spray liquid film characteristics and spray impact efficiency do not significantly change. In addition to that a single 2D axisymmetric simulation can take 2-3 days to get a fully converged solution for a 10-15 ms spraying process which is very efficient compared to a full 3D spray simulation (which can take several months for similar conditions).

In conclusion, a 2D axisymmetric model is used for the spray simulations using a full cone nozzle which will be presented in the next section of this paper.
Figure 14. Comparison of full 3D (on the left column, perspective view) and 2D axisymmetric (on the right column, vertical plane view) spray droplet velocity distribution for Case 1 ($h = 40$ mm, $\theta = 10^\circ$) from time, $t = 0 - 2.5$ ms. (Particles are colored by the velocity magnitude—dark blue refers to lower velocity range and red refers to higher velocity range (26-29.7 m/s), and time ($t$) in ms)
Figure 15. Comparison of full 3D (on the left column, perspective view) and 2D axisymmetric (on the right column, vertical plane view) spray droplet velocity distribution for Case 1 ($h = 40$ mm, $\theta = 10^\circ$) from time, $t = 3.5$ - 6 ms. (Particles are colored by the velocity magnitude—dark blue refers to lower velocity range and red refers to higher velocity range (26-29.7 m/s), and time ($t$) in ms)
C. Full Cone 2D Axisymmetric Sprays

Given the good agreement of the Case 1 and Case 2 2D axisymmetric and full 3D simulations, the remaining simulations are performed with a 2D axisymmetric formulation. The parameters of the full cone nozzle are assigned based on the Spraying Systems 1/8 G nozzle which is being used in the experimental part of this project. The optimum size of computational cells at the spray region is obtained based on parametric studies using 2D axisymmetric full cone sprays. The smallest computational cells are defined at the spray nozzle and the spray impact regions using the adaptive mesh refinement method (Fig. 16). The spray sub-models (e.g. droplet breakup models, atomization models) and turbulence model are chosen again based on initial parametric spray simulations which are not reported in this paper. The initial and boundary conditions of the 2D axisymmetric spray model are shown in Figure 16 with the important spray parameters. The boundary condition at the maximum radius is a constant pressure outlet rather than a solid wall as in the previous simulations. The computational domain is 50 mm high and has a radius of 50 mm. Effects of varying nozzle-to-surface distance (h), spray half angle (θ), spray mass flow rate (M), gravity (g), liquid surface tension (σ), liquid density (ρ) and liquid viscosity (μ) are studied as shown in Table 2. Table 3 shows the properties of spray liquid that are used in these calculations. HypV is a hypothetical liquid which has same physical properties as water at room temperature except viscosity. HypST is also a hypothetical liquid having same physical properties as water except surface tension, and similarly HypD is another hypothetical liquid having same physical properties as water except density.

![Diagram of Spray Parameters](image)

Figure 16. Initial, boundary conditions, computational cells and representative spray parameters for the 2D axisymmetric full cone spray cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Gravity (m/s²)</th>
<th>Spray Liquid</th>
<th>Mass Flow Rate, M (kg/s)</th>
<th>Nozzle-to-Surface, h (mm)</th>
<th>Spray Half Angle, θ (°)</th>
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Table 2. Parameters of the 2D axisymmetric full cone spray cases.

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Table 3. Properties of spray liquids.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Spray Liquid</th>
<th>Density (kg/m³)</th>
<th>Dynamic Viscosity (kg/m.s)</th>
<th>Surface Tension (N/m)</th>
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</thead>
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<td>I</td>
<td>HypV</td>
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<td>0.072</td>
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</table>

C.1. Effects of Varying Nozzle-to-Surface Distance (h)

Comparisons of Cases A, B and C reveal the effects of nozzle-to-surface distance (h) on spray characteristics. Case A is the spray which is injected from the closest distance to the impact surface (h = 25.4 mm), Case C is injected from the farthest (h = 38.1 mm) distance and Case B has the intermediate injection distance h = 31.75 mm. The spray half angle \( \theta = 26.5° \) is constant for Cases A, B and C.

Figure 17 shows the average drop diameters \( d_{32} \) (Fig. 17.a) and \( d_{10} \) (Fig. 17.b) for Cases A, B and C. Since the initial impact time is different for all three cases, the mean diameters are different at the beginning (0-2 ms). However, after the sprays impact the surface, the average drop diameters become very similar. Figure 18.a shows the spray liquid film mass (\( m_s \)) accumulation on the impact surface and Figure 18.b shows the spray impact efficiency (\( \eta \)) for Cases A, B and C. The liquid film mass and spray impact efficiency show similar trends for all cases. Case A has higher spray impact efficiency than Cases B and C. For instance, the Case A spray impact efficiency is 15% higher than Case C at \( t = 10 \) ms. These difference on the spray impact efficiency can be explained by less mass in the spray for the closer nozzle. The drop velocity and diameter distributions for Case A (Fig. 19.a) and Case C (Fig. 19.b) are shown in Figure 19. In Figure 19, one half shows velocity and the other half shows the diameter distribution. These full cone nozzle sprays show behavior which is similar to the previous pressure swirl type nozzle spray simulations. Drop velocity decreases as the spray approaches the impact surface and the splashing drops are slower and smaller compared to the initial spray drops (Fig. 19).

Figure 17. (a) The Sauter mean drop diameter (\( d_{32} \)) (b) the arithmetic mean drop diameter (\( d_{10} \)) for Case A (\( h = 25.4 \) mm), Case B (\( h = 31.75 \) mm) and Case C (\( h = 38.1 \) mm).
Spray impact efficiency, $\eta$ (%)

![Graph showing spray impact efficiency](image)

Figure 18. (a) The liquid film mass ($m_f$) accumulation (b) the spray impact efficiency ($\eta$) for Case A ($h = 25.4$ mm), Case B ($h = 31.75$ mm) and Case C ($h = 38.1$ mm) with $\theta = 26.5^\circ$.

![Graph showing droplet velocity and diameter](image)

Figure 19. Spray drops velocity and diameter distributions for (a) Case A ($h = 25.4$ mm) and (b) Case C ($h = 38.1$ mm) with same spray half angle, $\theta = 26.5^\circ$. (Note: the results are shown at the equal effective time which is $t_{eff} = t - t_{impact} = 6.5$ ms for both cases. $g$ refers to gravity. Left part of images: Red refers to faster (also fastest) droplets (18-20 m/s) while dark blue refers to slower (also slowest) droplets (0-2 m/s). Right part of images: Green refers to bigger droplets (0.11-0.155 mm) while dark blue refers to smaller droplets (0.002-0.026 mm))

C.2. Effects of Varying Spray Half Angle ($\theta$)

In order to compare the effects of spray half angle ($\theta$), Case D was simulated. Case D has the same nozzle-to-surface distance as Case C ($h = 38.1$ mm) but it has a smaller spray half angle, $\theta = 20.5^\circ$. Figure 20 shows the average drop diameters $d_{25}$ (Fig. 20a) and $d_{10}$ (Fig. 20b) for Cases C and D. The average drop diameters are not as similar in Cases A, B and C. The narrower spray has slightly larger average drops. Figure 21a shows the liquid film mass ($m_f$) accumulation on the surface and Figure 21b shows the spray impact efficiency ($\eta$) for Cases C and D. The liquid film mass and the spray impact efficiency show similar trends for both cases, but Case D has more liquid film mass and higher impact efficiency at later time. The drop velocity and diameter distributions for Case C (Fig. 22a) and Case D (Fig. 22b) are shown in Figure 22. One half of each figure shows the velocity and the other half shows the diameter distribution. Similar to the other spray cases, the drop velocity decreases as the spray approaches the impact surface and the splashing drops are slower and smaller compared to the initial spray drops (Fig. 22).
Figure 20. (a) The Sauter mean drop diameter ($d_{32}$) (b) the arithmetic mean drop diameter ($d_{10}$) for Case C ($\theta = 26.5^\circ$) and Case D ($\theta = 20.5^\circ$) with $h = 38.1$ mm.

Figure 21. (a) The liquid film mass ($m_s$) accumulation (b) the spray impact efficiency ($\eta$) for Case C ($\theta = 26.5^\circ$) and Case D ($\theta = 20.5^\circ$) with $h = 38.1$ mm.

Figure 22. The droplet velocity and diameter distributions for (a) Case C ($\theta = 26.5^\circ$) (b) Case D ($\theta = 20.5^\circ$) with same nozzle-to-surface distance, $h = 38.1$ mm. (Note: the results are shown at the equal effective time which is $t_{eff} = t - t_{impact} = 6.5$ ms for both cases. Left part of images: Red refers to faster (also fastest) droplets (18-20 m/s) while dark blue refers to slower (also slowest) droplets (0-2 m/s) Right part of images: Green refers to bigger droplets (0.11-0.155 mm) while dark blue refers to smaller droplets (0.002-0.026 mm))
C.3. Effects of Varying Gravity (g)

In order to compare the effects of gravity (g) on sprays, Cases E and F was simulated. Cases E and F have same spray parameters as Case C except gravity. Case C has gravity equal to Earth gravity (\( g = -9.81 \text{ m/s}^2 \)), Case E has gravity equal to Solar gravity (\( g = -275 \text{ m/s}^2 \)) and Case F has gravity equal to Earth gravity in the opposite direction, away from the impact surface (\( g = +9.81 \text{ m/s}^2 \)). Figure 23 shows the average drop diameters \( d_{32} \) (Fig. 23.a) and \( d_{10} \) (Fig. 23.b) for Cases C, E and F. The average drop diameters are similar but smaller drops occur in Case E (Solar gravity). Figure 24.a shows the liquid film mass (\( m_s \)) accumulation on the surface and Figure 24.b shows the spray impact efficiency (\( \eta \)) for Cases C, E and F. The liquid film mass and the spray impact efficiency show very similar trends for these cases, but Case E has slightly higher film mass and impact efficiency.

Figure 23. (a) The Sauter mean drop diameter (\( d_{32} \)) (b) the arithmetic mean drop diameter (\( d_{10} \)) for Case C (\( g = -9.81 \text{ m/s}^2 \)), Case E (\( g = -275 \text{ m/s}^2 \)) and Case F (\( g = +9.81 \text{ m/s}^2 \)). (Note that negative sign means gravity acting toward the surface)

Figure 24. (a) The liquid film mass (\( m_s \)) accumulation (b) the spray impact efficiency (\( \eta \)) for Case C (\( g = -9.81 \text{ m/s}^2 \)), Case E (\( g = -275 \text{ m/s}^2 \)) and Case F (\( g = +9.81 \text{ m/s}^2 \)).
C.4. Effects of Varying Spray Mass Flow Rate ($M$)

The effects of varying mass flow rate ($M$) on sprays have been studied for Cases C, G and H. Cases G and H have same spray parameters as Case C except the spray mass flow rate. Case C has spray mass flow rate, $M = 0.01207$ kg/s, Case G has $M = 0.01514$ kg/s (the highest mass flow rate) and Case H has $M = 0.004$ kg/s (the lowest mass flow rate). Figure 25 shows the average drop diameters $d_{32}$ (Fig. 25.a) and $d_{10}$ (Fig. 25.b) for Cases C, G and H. The spray with the highest mass flow rate (Case G) has the biggest drops whereas the spray with the lowest mass flow rate (Case H) has the smallest drops (Fig. 25.a and Fig. 25.b). Figure 26.a shows the liquid film mass ($m_s$) accumulation on the surface and Figure 26.b shows the spray impact efficiency ($\eta$) for Cases C, G and H. The lowest mass flow rate (Case H) has the least liquid film accumulation on the surface and the highest mass flow rate (Case G) has the most liquid film accumulation on the surface (Fig. 26.a). However, the spray impact efficiency shows similar trends for all mass flow rate cases, and the lowest mass flow rate case (Case H) has a lower impact efficiency than other cases (Fig. 26.b).

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**Figure 25.** (a) The Sauter mean drop diameter ($d_{32}$) (b) the arithmetic mean drop diameter ($d_{10}$) for Case C ($M = 0.01207$ kg/s), Case G ($M = 0.01514$ kg/s) and Case H ($M = 0.004$ kg/s).

**Figure 26.** (a) The liquid film mass ($m_s$) accumulation (b) the spray impact efficiency ($\eta$) for Case C ($M = 0.01207$ kg/s), Case G ($M = 0.01514$ kg/s) and Case H ($M = 0.004$ kg/s).
C.5. Effects of Varying Spray Liquid Viscosity ($\mu$)

The effects of varying liquid viscosity ($\mu$) on sprays have been studied for Cases C and I. Case I has same spray parameters as Case C except the liquid viscosity. Case I has a hypothetical liquid (HypV) with a viscosity 5 times larger than water viscosity at room temperature ($\mu = 0.001$ kg/m.s). Figure 27 shows the average drop diameters $d_{32}$ (Fig. 27.a) and $d_{10}$ (Fig. 27.b) for Cases C and I. The more viscous spray (Case I) has significantly bigger drops compared to the less viscous spray (Case C). Figure 28.a shows the liquid film mass ($m_s$) accumulation on the surface and Figure 28.b shows the spray impact efficiency ($\eta$) for Cases C and I. The liquid film accumulation on the surface and the spray impact efficiency shows quite similar trends (Fig. 28).

Figure 27. (a) The Sauter mean drop diameter ($d_{32}$) (b) the arithmetic mean drop diameter ($d_{10}$) for Case C (water: $\mu = 0.001$ kg/m.s) and Case I (HypV: $\mu = 0.005$ kg/m.s).

Figure 28. (a) The liquid film mass ($m_s$) accumulation (b) the spray impact efficiency ($\eta$) for Case C (water: $\mu = 0.001$ kg/m.s) and Case I (HypV: $\mu = 0.005$ kg/m.s).
C.6. Effects of Varying Spray Liquid Surface Tension ($\sigma$)

The effects of varying liquid surface tension ($\sigma$) on sprays have been studied for Cases C and J. Case J has the same spray parameters as Case C (water) except the liquid surface tension. Case J uses a hypothetical liquid (HypST) with surface tension equal to 0.01 N/m which is less than water at room temperature ($\sigma = 0.072$ N/m). Figure 29 shows the average drop diameters $d_{32}$ (Fig. 29.a) and $d_{10}$ (Fig. 29.b) for Cases C and J. A lower surface tension (Case J) results in much smaller drops. Figure 30.a shows the liquid film mass ($m_s$) accumulation on the surface and Figure 30.b shows the spray impact efficiency ($\eta$) for Cases C and J. Initially, there is more liquid film mass accumulation on the surface for the high surface tension liquid (water, Case C) but eventually the liquid film mass becomes comparable for both cases. However, the higher surface tension liquid (water, Case C) has a larger impact efficiency.

Figure 29. (a) The Sauter mean drop diameter ($d_{32}$) (b) the arithmetic mean drop diameter ($d_{10}$) for Case C (water: $\sigma = 0.072$ N/m) and Case J (HypST: $\sigma = 0.01$ N/m).

Figure 30. (a) The liquid film mass ($m_s$) accumulation (b) the spray impact efficiency ($\eta$) for Case C (water: $\sigma = 0.072$ N/m) and Case J (HypST: $\sigma = 0.01$ N/m).
C.7. Effects of Varying Spray Liquid Density ($\rho$)

The effects of varying liquid density ($\rho$) on sprays have been studied for Cases C and K. Case K has the same spray parameters as Case C (water) except the liquid density. HypD is a hypothetical liquid with density equal to 3000 kg/m$^3$, which is around 3 times more than water density at room temperature ($\rho = 998$ kg/m$^3$). Figure 31 shows the average drop diameters $d_{32}$ (Fig. 31.a) and $d_{10}$ (Fig. 31.b) for Cases C and K. The more dense liquid (Case K) results in much smaller drops compared to the less dense water (Case C). Figure 32.a shows the liquid film mass ($m_s$) accumulation on the surface and Figure 32.b shows the spray impact efficiency ($\eta$) for Cases C and K. There is more liquid film mass accumulation on the surface for the less dense liquid (water, Case C). Higher impact efficiency occurs with less dense liquid (water, Case C) compared to more dense (HypD, Case K). These results suggest that there is much more splashing with the more dense liquid.

Figure 31. (a) The Sauter mean drop diameter ($d_{32}$) (b) the arithmetic mean drop diameter ($d_{10}$) for Case C (water: $\rho = 998$ kg/m$^3$) and Case K (HypD: $\rho = 3000$ kg/m$^3$).

Figure 32. (a) The liquid film mass ($m_s$) accumulation (b) the spray impact efficiency ($\eta$) for Case C (water: $\rho = 998$ kg/m$^3$) and Case K (HypD: $\rho = 3000$ kg/m$^3$).

Figure 33 shows the effects of all the basic parameters mentioned previously on the total number of spray drops. For the conditions studied, these effects can be briefly summarized as:

- Increasing the nozzle-to-surface ($h$) distance increases the total number of drops (Fig. 33.a).
- Increasing the spray half angle ($\theta$) increases the total number of drops (Fig. 33.b).
- Increasing gravity ($g$) by a factor of 28 slightly increases the total number of drops (Fig. 33.c).
- Reversing the direction of Earth gravity has a negligible effect (Fig. 33.c).
- Increasing the mass flow rate ($M$) increases the total number of drops (Fig. 33.d).
- Increasing the liquid viscosity decreases the total number of drops (Fig. 33.e).
- Increasing the surface tension greatly decreases the total number of drops (Fig. 33.f).
- Increasing the liquid density also greatly increases the total number of drops (Fig. 33.f).

Figure 33. Effects of basic spray parameters on total number of drops (N).
IV. Conclusions

This paper reports the spray model and the results obtained from 3D and 2D axisymmetric isothermal spray simulations under turbulent flow conditions using the Discrete Phase Model (DPM) in the current version of FLUENT. The pressure-swirl atomizer model is utilized to create swirling hollow cone spray patterns for full 3D and 2D axisymmetric domains. Comparison of these results justifies the use of the 2D axisymmetric model. Full cone sprays based on the nozzle used by the WVU experimental group are studied using the 2D axisymmetric model. The velocity and diameter distributions of the spray drops, mass of the liquid film that has accumulated on the impact surface, and the spray impact efficiency are studied by varying gravity, spray mass flow rate, nozzle-to-surface distance, spray half angle, and spray liquid properties (density, surface tension and viscosity). Additional simulations need to be performed at longer spraying times for each of the spray parameters, but it can be concluded based on the cases investigated that the spray impact efficiency can be increased under these conditions:

- Smaller nozzle-to-surface distance ($b$) based on Case C (parameters of Case C is explained in Table 2),
- Smaller spray half angle ($\theta$) based on Case C,
- Spraying at higher gravity ($g$): a lower Froude ($Fr$) number ($Fr = V^2 / g.d$) based on Case C,
- Higher spray mass flow rate ($M$) based on Case C,
- More viscous liquid ($\mu$): a lower Reynolds ($Re$) number ($Re = \rho. V.d / \mu$) based on Case C,
- Higher surface tension of liquid ($\sigma$): a lower Weber ($We$) number ($We = \rho. V^2.d / \sigma$) based on Case C,
- Smaller density (less dense) of liquid ($\rho$): a lower Reynolds ($Re$) number ($Re = \rho. V.d / \mu$) based on Case C.

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References