Film Thickness and Velocity Distribution in a Splash-Plate Atomizer: Comparison between Simulations and Experiments

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A 3D computational model is presented for the simulation of fluid flow and spray in a splash-plate atomizer. The model combines the solution of continuity and momentum equations with an algorithm for free surface tracking in presence of an arbitrary nozzle shape. The model simulates the flow through the nozzle and predicts the formation of a liquid film and spray droplet size at the nozzle exit. Close agreement between numerical results and measurements for film thickness and velocity distributions validates the model and its underlying assumptions. The effect of viscosity on liquid film thickness and velocity is also investigated; for a liquid with a higher viscosity, the liquid film is thicker and its velocity is smaller.

1. Introduction

In a splash-plate atomizer, a flat plate of usually rounded cross-section is attached at an angle to the end of a liquid carrying pipe. The liquid flows through the pipe and when it exits from the end of the pipe it strikes the flat face of the plate at an angle. The flow is turned and flattened into a film of liquid. The film leaves the plate and breaks up into ligaments and droplets.

Splash-plate atomizers are widely used in recovery boilers where the use of slurries such as black liquor from wood pulp is utilized in combustion systems as an alternative to oil and gas. Spray droplet size and size distribution are key variables in controlling spray combustion in these systems. Splash-plate atomizers are designed based on experimental measurements. Because of the complexity of the flows existing in these systems, there is no accurate technique that can relate the nozzle design to the spray droplet size and velocity distribution. To better understand the performance of a particular nozzle, the determination of the droplet size distribution is critical. This particle size distribution is usually determined by physical experimentation in spray booth, using either black liquor or corn syrup. Most spray nozzles are characterized in ambient conditions and may not provide the same results under different conditions. If a computer code makes it possible to see the resulting spray of a specific nozzle design, it will be of great interest to any one working in this field. Such a code can be used to: design new nozzles; improve current nozzle designs; obtain the spraying characteristics of a nozzle such as mean droplet size, droplet size distribution, spray angle, spray pattern, mixing within the spray, droplet velocity in a certain distance from the nozzle exit; and investigate the spraying characteristics of a nozzle under different operating conditions.

We have developed a computer code than can predict the liquid film characteristics and spray droplet size distribution in a splash-plate atomizer. We use a 3D numerical model that combines the solution of Navier-Stokes equations with an algorithm for tracking the liquid free surface in presence of an arbitrary obstacle shape in the computational domain. To validate the model, we compared simulation results with experimental measurements for the film thickness and velocity distribution in a typical splash-plate nozzle. In this paper, we present the details of this comparison.

2. Numerical Method

2.1. Fluid Flow

Fluid flow in a splash-plate atomizer is modeled using a finite volume solution of the Navier-Stokes equations in a 3D Cartesian coordinate system assuming laminar, incompressible flow. The surface profile of the deforming liquid is defined using the "fractional volume of fluid" scheme where a scalar function f is defined as the fraction of a cell volume occupied by fluid. f is assumed to be unity when a cell is fully occupied by the fluid and zero for an empty cell. Cells with values of $0<f<1$ contain a free surface. Surface tension is modeled as a volume force acting on fluid near the free surface. Details of the fluid flow model are given by Bussmann et al. [1].

2.2. Nozzle Body

The body of the splash-plate nozzle in the computational domain is a complex internal obstacle that affects the fluid flow. We treat internal obstacles by defining a liquid/obstacle volume fraction Θ, a scalar field whose value is equal to one in the fluid and zero in the obstacle. Cells having a value of Θ satisfying $0<\Theta<1$ are termed "partial flow cells" because a portion Θ of their volume is open to flow and the remaining portion ($1-\Theta$) is occupied by an obstacle closed to flow. The obstacle is characterized as a fluid with infinite density and zero velocity. In the presence of internal obstacles, the finite volume approximations of the fluid flow equations are modified by defining a volume fraction Θ at the cell center, and area fractions Θ_x, Θ_y and Θ_z at the cell faces in the x, y and z directions, respectively. Boundary conditions that must be imposed on the liquid/obstacle interface are velocity boundary conditions. No-slip conditions on this interface are applied by defining "fictitious" velocities within obstacle cells adjacent to fluid cells. Velocities at the faces of these cells are set such that normal and tangential velocities at the liquid/obstacle interface become zero (no-slip condition). Details of the computational treatment of internal obstacles are given elsewhere [2] and will not be repeated here.

Numerical computations were performed on a PC with 1 GHz clock speed and 2 GB RAM. A typical CPU time, depending on the nozzle shape and conditions of the simulation, ranged from a few hours to a few days.

3. Results

We ran simulations for a splash-plate atomizer for which the experimental results were available in the literature. Obuskovic and Adams [3] performed experiments on B&W (Babcock & Wilcox) splash-plate nozzles. They measured both the liquid film thickness and the velocity of the top surface of the film close to the rim of a splash-plate nozzle as functions of nozzle exit velocity and liquid viscosity. We ran simulations for one of the nozzles considered in their paper [3]: a 15-52 B&W splash-plate nozzle. The nozzle shape is seen in the first sequence of Fig. 1. The operating conditions considered in experiments and simulations are as follows:

Nozzle: B&W 15-52
Liquid: corn syrup ; density 1360 kg/m^3 ; surface tension 0.02 N/m
Jet: diameter 11.9 mm ; velocity 7.1 m/s ; angle of impact 52^o

The splash-plate we considered in simulation had an oval shape 60 mm in length and 48 mm in width. Corn syrup is a liquid with solid contents; changing the amount of solid content changes the viscosity. The experiments were performed for two different values of viscosity: 175 mPa-s and 325 mPa-s. It should be mentioned that corn syrup is known to be a Newtonian fluid over this range of viscosity [3]. In this section, we present and discuss numerical results for these two cases, and provide a comparison with the corresponding experimental measurements [3].

3.1. Case 1: Liquid viscosity of 175 mPa-s

A 3D view of the simulation results for the evolution of liquid flow into the splash-plate nozzle when the viscosity of corn syrup was assumed to be 175 mPa-s is shown in Fig. 1. Boundaries of the computational domain were assumed open boundaries through which the liquid film could pass. The jet flow impacts on the splash-plate 5 ms after it is introduced to the nozzle. The liquid film spreads to the front and the two sides of the splash-plate. Wave formation on the liquid film breaks it up shortly after it leaves the rim of the plate.

To validate the numerical results with experimental measurements, we compared the liquid film thickness and top surface velocity close to the rim of the plate at three different angles from the plate centerline. A close-up of the numerical results for liquid film and its velocity distributions on these cross-sections are presented in Fig. 2. The three considered angles and their corresponding cross-sectional planes are shown in Fig. 3. Since experimental measurements [3] are available close to the rim of the splash-plate, in Fig. 2 the liquid film and its velocity are shown in the same location so we can compare the two results. What follows is the detail of the comparison of numerical and experimental results:

<u>At 0^o angle from the plate centerline:</u>

Film thickness: from experiment (figure 5 of Ref. 3 using an extrapolation) ≈ 1.9 mm
from numerical results (Fig. 2a) ≈ 2 mm

Film top surface velocity: from experiments (figure 6 of Ref. 3 using an extrapolation) ≈ 6 m/s
from numerical results (Fig. 2a) ≈ 6.3 m/s

<u>At 25^o angle from the plate centerline:</u>

Film thickness: from experiment (figure 5 of Ref. 3) ≈ 1.8 mm
from numerical results (Fig. 2b) ≈ 1.9 mm

Film top surface velocity: from experiments (figure 6 of Ref. 3) ≈ 5.7 m/s
from numerical results (Fig. 2b) ≈ 6.0 m/s

<u>At 50^o angle from the plate centerline:</u>

Film thickness: from experiment (figure 5 of Ref. 3) ≈ 1.7 mm
from numerical results (Fig. 2c) ≈ 1.7 mm

Film top surface velocity: from experiments (figure 6 of Ref. 3) ≈ 3.9 m/s
from numerical results (Fig. 2c) ≈ 5.2 m/s

3.2. Case 2: Liquid viscosity of 325 mPa-s

We ran another simulation for the same nozzle given in Fig. 1 but using a viscosity of 325 mPa-s for corn syrup. All other conditions and input to the code are the same as for the previous case. Figure 4 shows a 3D view of the simulation results for the evolution of liquid flow into the splash-plate nozzle in this case. Compared to the previous case with lower viscosity (Fig. 1): the liquid film is more stable with less surface waves in the azimuthal direction; more liquid moves to the sides; and as a result, a thicker liquid edge on the two sides of the liquid film is observed.

We performed the same comparison with experiments [3] for this case as we did for the previous case. The close up of the numerical results at the three cross-sections are shown in Fig. 5, and here is the detail of the comparison between numerical results and experimental measurements:

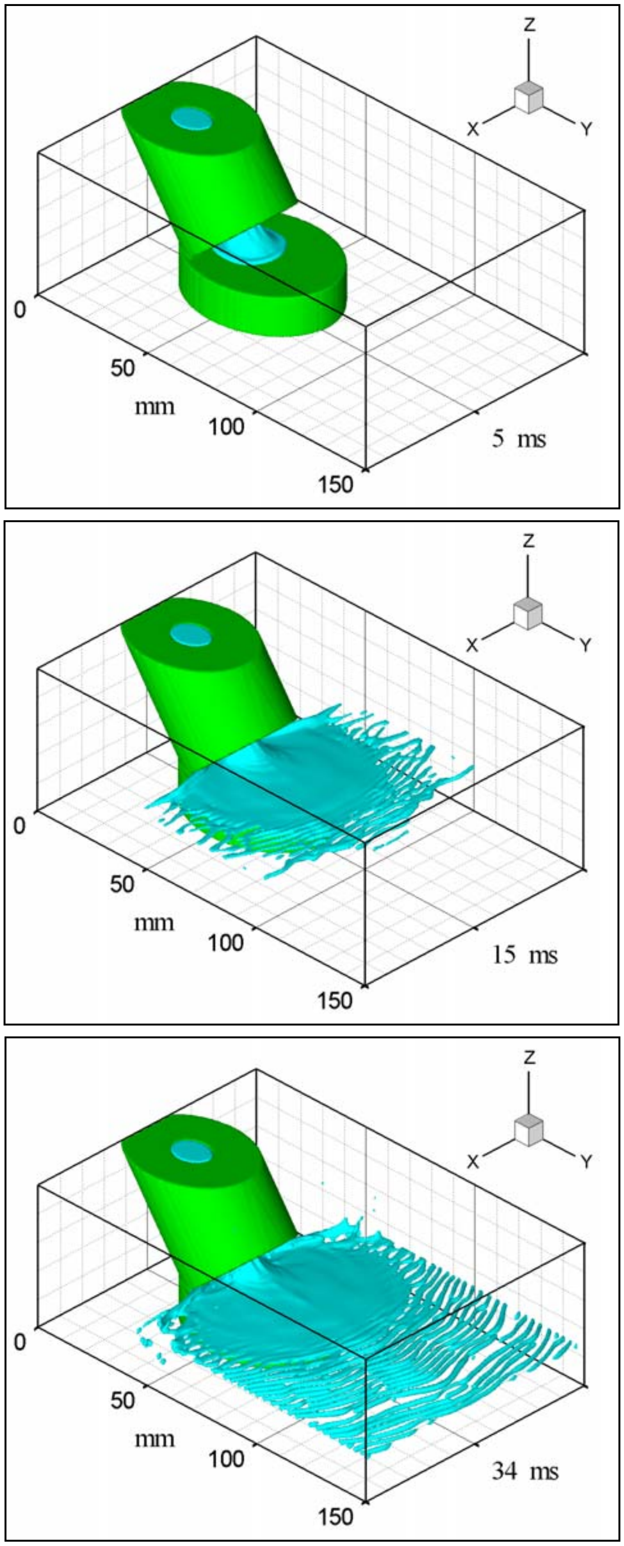

Figure 1. 3D view of the evolution of a corn syrup liquid flow into the splash-plate nozzle with a velocity of 7.1 m/s. The viscosity of corn syrup for this simulation was assumed **175** mPa-s.

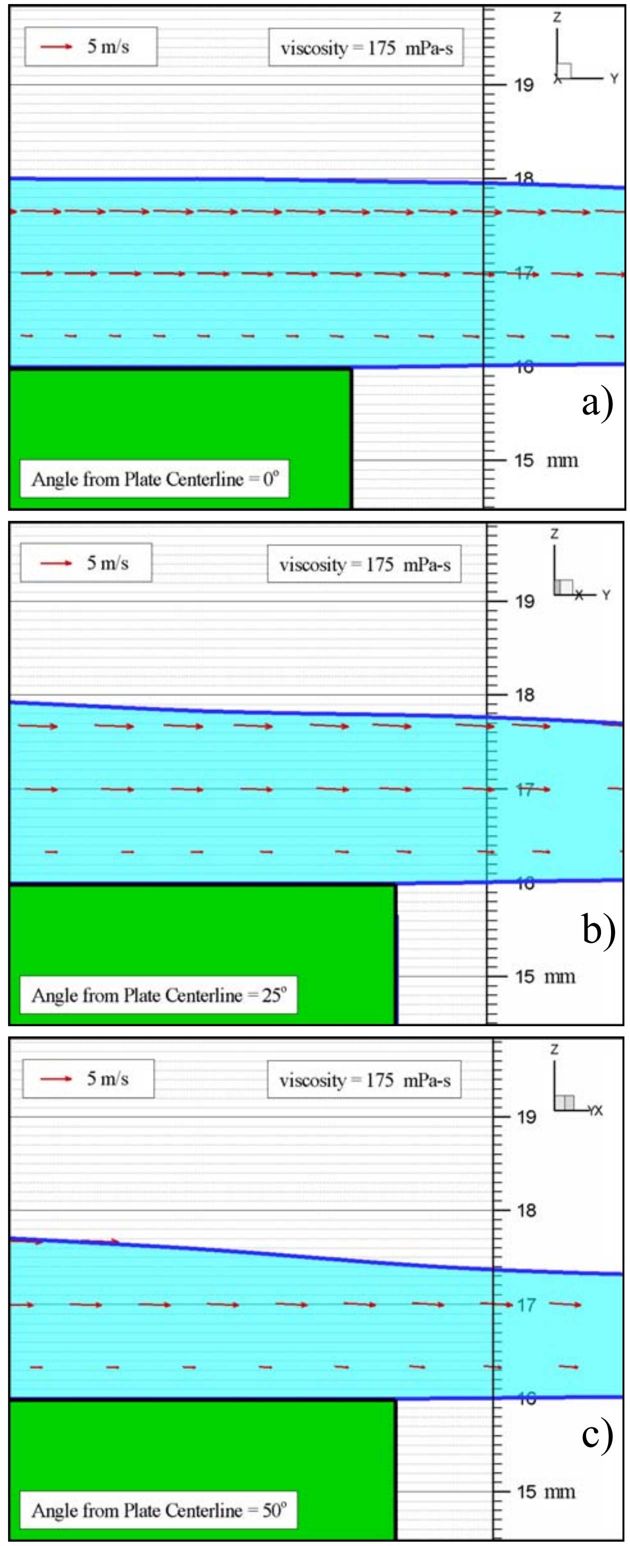

Figure 2. A close-up of the numerical results for liquid film and its velocity distributions on three cross-sections shown in Fig. 3 at a) 0°, b) 25°, and c) 50° angle from the plate centerline. The nozzle jet velocity was 7.1 m/s and the viscosity of corn syrup was assumed **175** mPa-s.

At 0^o angle from the plate centerline:

Film thickness: from experiment (figure 5 of Ref.3 using an extrapolation) ≈ 2.3 mm
from numerical results (Fig. 5a) ≈ 2.4 mm

Film top surface velocity: from experiments (figure 6 of Ref.3 using an extrapolation) ≈ 4.5 m/s
from numerical results (Fig. 5a) ≈ 5.2 m/s

At 25^o angle from the plate centerline:

Film thickness: from experiment (figure 5 of Ref.3) ≈ 2.2 mm
from numerical results (Fig. 5b) ≈ 2.1 mm

Film top surface velocity: from experiments (figure 6 of Ref.3) ≈ 4.2 m/s
from numerical results (Fig. 5b) ≈ 4.9 m/s

At 50^o angle from the plate centerline:

Film thickness: from experiment (figure 5 of Ref.3) ≈ 2.0 mm
from numerical results (Fig. 5c) ≈ 2.0 mm

Film top surface velocity: from experiments (figure 6 of Ref.3) ≈ 2.8 m/s
from numerical results (Fig. 5c) ≈ 4.3 m/s

4. Discussion

In order to show the comparison between the numerical results and measurements [3], we plotted both results for the two cases in the same frame as presented in Fig. 6. Figure 6a shows the film thickness, and Fig. 6b shows the film top surface velocity against the angle from the plate centerline.

As observed in Fig. 6a, both simulations and experiments show that for the case with higher viscosity, the liquid film is thicker. This is because when the viscosity is increased, more liquid momentum is lost due to viscous dissipations; therefore, the velocity of the film at the rim of the splash-plate is decreased (Fig. 6b). Since the nozzle flow rate for both cases are equal (i.e. the jet velocity is the same for both cases of low and high viscosities), the film for the more viscous liquid will be thicker (Fig. 6a).

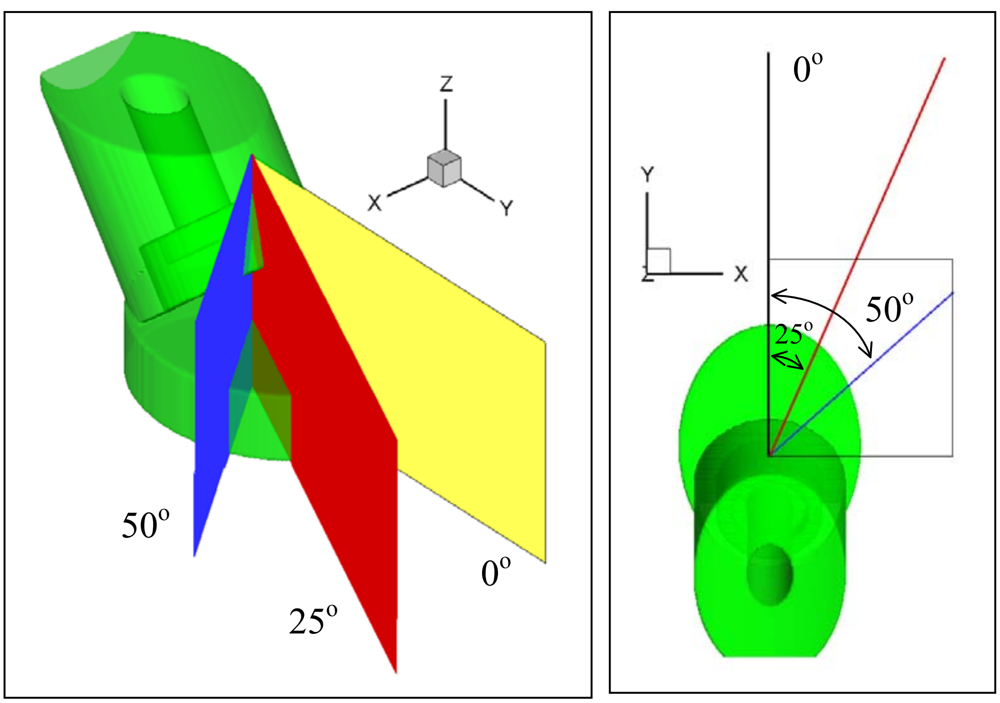

Figure 3. Three different angles from the plate centerline and their corresponding cross-sectional planes of the splash-plate nozzle. Comparison between the results of simulation with available experimental measurements [3] was performed on these cross sections.

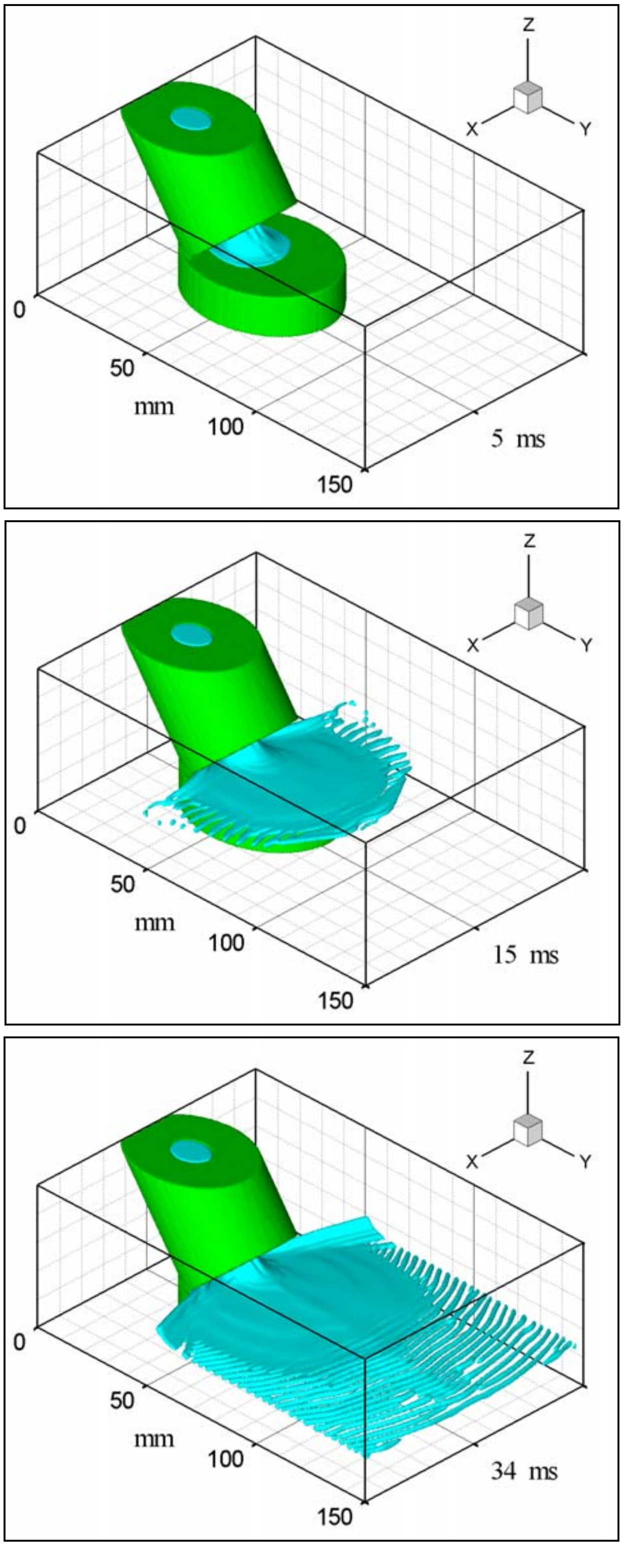

Figure 4. 3D view of the evolution of a corn syrup liquid flow into the splash-plate nozzle with a velocity of 7.1 m/s. The viscosity of corn syrup for this simulation was assumed **325** mPa-s.

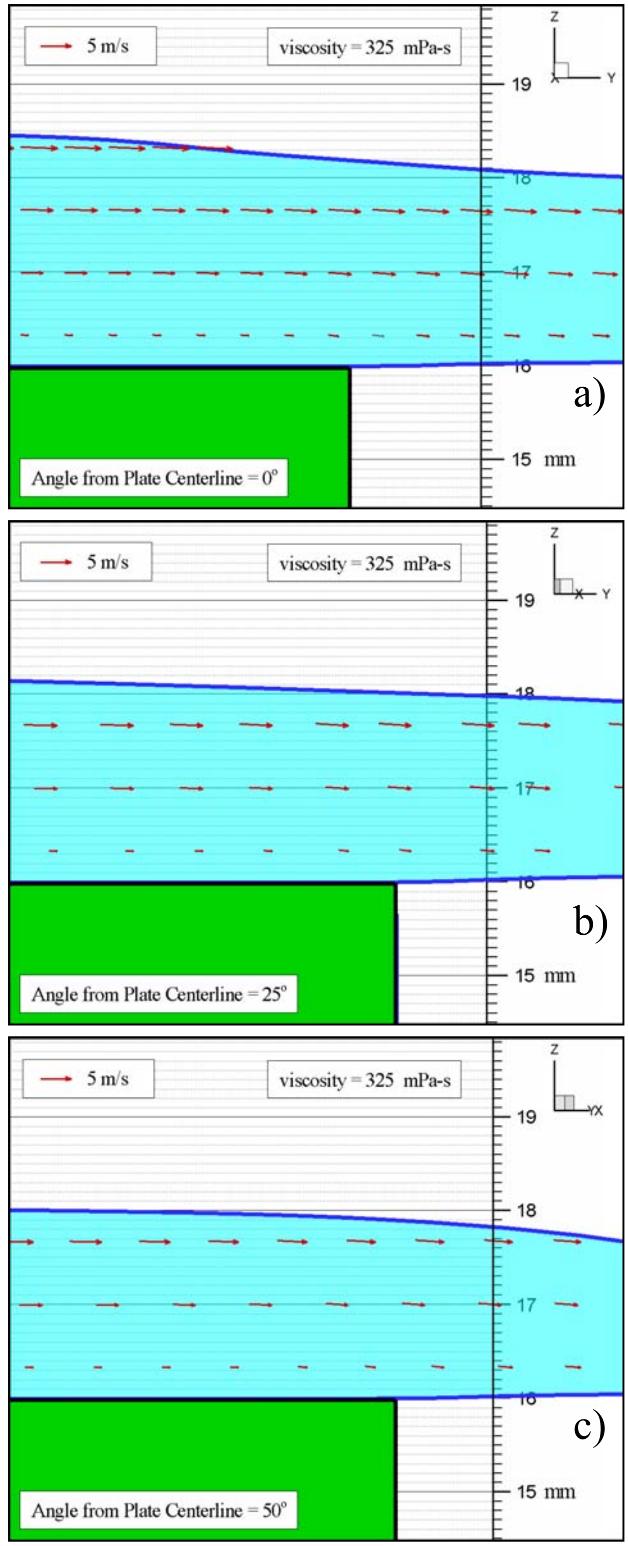

Figure 5. A close-up of the numerical results for liquid film and its velocity distributions on three cross-sections shown in Fig. 3 at a) 0°, b) 25°, and c) 50° angle from the plate centerline. The nozzle jet velocity was 7.1 m/s and the viscosity of corn syrup was assumed **325** mPa-s.

For both cases, at a higher angle from the plate centerline, the film thickness and velocity are decreased (Fig. 6). This is because the liquid jet impacts the plate with an angle (52^o here); therefore, more liquid flows close to the centerline. At a normal impingement of a liquid jet on a plate, film thickness and its velocity will be uniform in the angular direction.

Comparisons between numerical simulations and measurements show that we have a close agreement between the two results for the film thickness in both cases. The difference is less than 5% (Fig. 6a). One important point regarding the numerical results (Figs. 2 and 5) is that across the film thickness at the rim of the splash-plate there is only three or four computational cells. This fact reveals the efficiency of the model that even with a small number of cells it could accurately predict the film thickness.

For the film top surface velocity, we have a good agreement at the angles close to the plate centerline. The difference is less than 5% for Case 1 (lower viscosity) and 14% for Case 2. There are, however, discrepancies between the two results for the top surface velocity at higher angles from the plate centerline. For example, at 50^o angle from the plate centerline, the discrepancy between the calculated and measured velocities is around 25% for the lower viscosity (Case 1) and 35% for the higher viscosity (Case 2). This discrepancy may be attributed to the uncertainties of the velocity measurements in the experiments [3] where the velocity of the random irregularities at the top surface of the film was measured and assumed to be the same as the film velocity. Moreover, as mentioned in Ref. 3, when measuring velocities, the alignment of the fibre optic probes with the direction of the flow is important. Any misalignment can change the measured velocity significantly. The importance of the alignment in the flow direction is more pronounced at higher angles from the plate centerline. The uncertainties of velocity measurements at higher angles can be shown by a close look at Fig. 6 (or more visibly at figures 5 and 6 of Ref. 3). While the measured film thickness changes smoothly with the angle from the centerline, the measured top surface velocity has a sudden change after 25^o angle.

The comparison performed in this paper between numerical results and experimental measurements [3] demonstrates the accuracy of the numerical model used in the developed code in predicting the film thickness and its velocity distributions for black liquor splash-plate atomizers. The model, therefore, can be used to predict the film characteristics behavior of a flow into a nozzle at different operating conditions, and also as a tool in the design of new nozzles.

5. Conclusions

A computer code has been developed to predict the liquid film characteristics in a splash-plate atomizer. To validate the model, we compared simulation results with experimental measurements for the film thickness and velocity distributions in a typical splash-plate nozzle. Close agreement between numerical results and measurements validated the model and its underlying assumptions. The developed code can be used to: improve the design of current nozzles, test new nozzle designs, and determine the effects of various parameters on the resulting film and spray of a nozzle.

Acknowledgements

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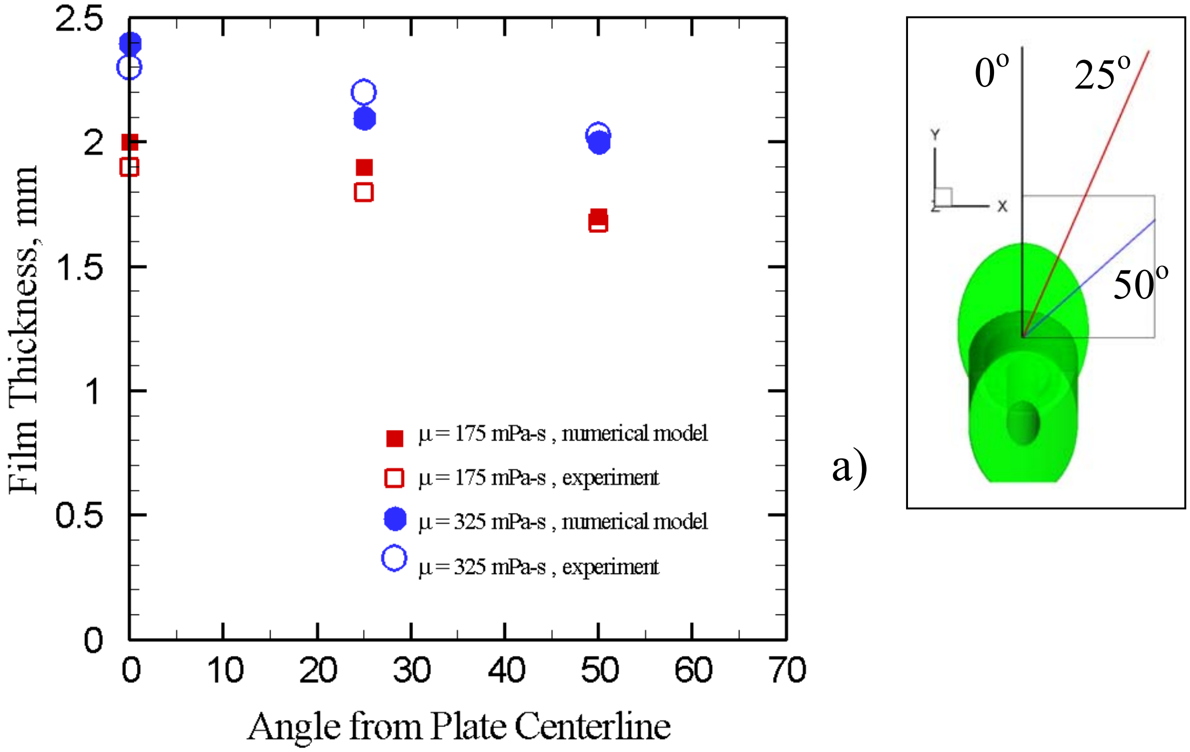

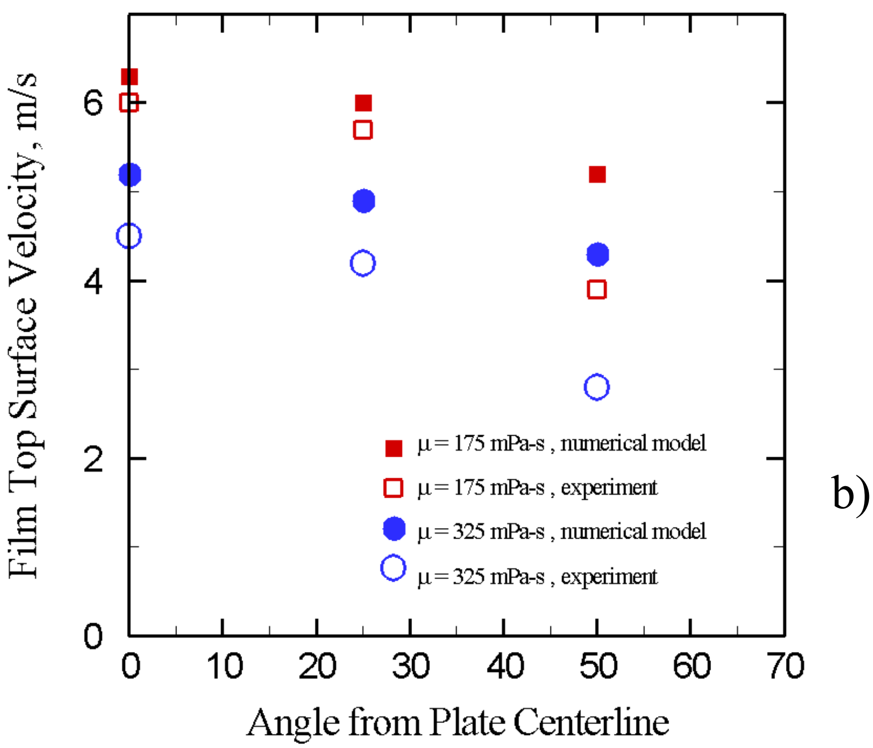

Figure 6. Comparison between the numerical results with available experimental measurements [3] for the splash-plate nozzle shown in Fig. 1 at two different viscosities. The results are compared for: a) the film thickness, and b) the film top surface velocity against the angle from the plate centerline. The nozzle jet velocity was 7.1 m/s.