INVESTIGATION OF UNSTEADY EFFECTS IN PRESSURE SWIRL ATOMIZERS

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Introduction

Pressure swirl atomizers are quite common due to their favorable atomization characteristics, low clogging tendency and geometrical simplicity: The fluid to be atomized enters through one, two or more tangential inlet ports, passes through the swirl chamber with a conical convergent part and exits through a cylindrical orifice. The high swirl velocity as well as the acceleration of the liquid through a convergent exit part produce an hollow conical liquid sheet as well as a gaseous core extending from the outlet through the swirl chamber mostly up to the top lid. After some distance downward the nozzle exit, the sheet becomes unstable and breaks up to form a spray of droplets. Although the geometrical characteristics are relatively simple, the inner flow pattern is rather complex. Though several authors tried to gain insight of the internal nozzle flow, there is still distinct lack of knowledge in this regard. Wang [1] and Jeng et al. [2] carried out experimental studies of a swirl atomizers. Jeng et al. [2] also performed a numerical simulation of two−dimensional, turbulent (Baldwin−Lomax model) nozzle model using moving grids for representing the free surface. The nozzle had the same geometry as used at UMIST (Yule,Cooper)[5][6]. The same kind of geometry was used in the references [6], [3], [8] as well. Results were limited to the comparison of nozzle characteristics such as spray angle, film thickness at nozzle exit and discharge coefficient. More recently, Lee and Steinthorsson [8] performed numerical simulations of internal flow in a three−dimensional simplex nozzle and used the same geometry as Jeng [2]. One fourth of the nozzle was simulated using 380,000 control volumes (CVs) and the VOF−method [8]. The resolution they employed was, however, still insufficient for the case treated; clearly, a larger number of cells was necessary.

The main problem that remains despite the above contributions is that there seems to be no general agreement even about the nature of the flow fields in a typical simplex nozzle. The present authors have not found any satisfactory definition of characteristic nondimensional reference numbers or expressions that would describe the flow or allow to discriminate between laminar and turbulent flow behavior, much less to decide where the possible transition takes place. H.D. Dahl [9] carried out theoretical and experimental investigations of simplex nozzles. His results are very useful for estimating flow properties for various nozzle geometries. However, due to the small amount of experimental data collected by him, no general conclusions can be drawn about a possible transition zone in the flow. In [4], various characteristic nondimensional numbers for describing the spraying properties of simplex nozzles have been proposed, but again, no evidence about the flow type has been indicated. The major drawback of all the above studies is that they mostly did not consider or investigate the unsteady behavior of the the nozzles and assumed steady flow instead. However, it has been observed repeatedly in experiments and computations that the corresponding flow displays a significant unsteady component.

Due to these reasons, it is still difficult to optimize the simplex nozzles without an intimate knowledge of the flow effects occurring in it. With this background in mind, the present authors decided to carry out a detailed phenomenological study of several models of typical pressurized simplex nozzles operated with water or glycerin in air. The present work was accomplished using numerical simulation methods, while still considering the respective experimental results obtained for the same configurations by other investigators [7,6]. The present numerical computations were performed on conventional clusters of PCs using the commercial Navier−Stokes solvers **COMET** and **FLUENT**.

Two−dimensional internal nozzle flow

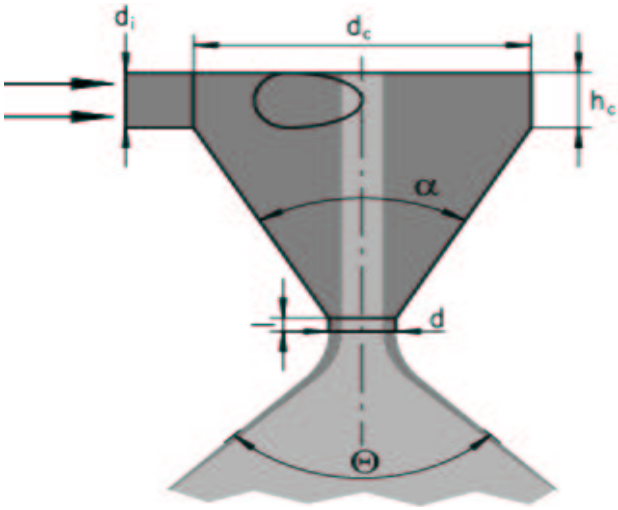
Initially, the numerical simulations were performed using two−dimensional axisymmetric models of the

simplex nozzles investigated by [5] and [7]. The corresponding geometry of the two nozzles studied here is displayed in Fig. 1 including all the important data. Two nozzles were analyzed numerically, possessing different geometries. The wastly different Reynolds−numbers, computed after Walzel [7] and denoted Re_W, were achieved using water and water−glycerin mixture. The swirl (tangential velocity component) had to be taken into account. It should be noticed that the present definition of the Reynolds number was mostly (unless otherwise specified) based on the work published by Walzel [7]. In the present authors opinion, this is the simpelst yet physically most meaningful definition that could be found in literature [5, 7, 8]. In the later part of the present work, however, the Reynolds−number definition by Yule and Cooper [5],[6], denoted here Re_Y, was also computed for comparison with the above experimental work. The free−surface between the liquid and gaseous phases has been modeled using an interface−tracking algorithm of VOF−type [11].

Small nozzle:

d_c = 50 mm
d_i = 2x7 mm
d = 15 mm
h_c = 7 mm
l/d = 1,0
α = 90°

Re_W = 100,000
ρ = 1,000 kg/m³
μ = 1×10^{-3} Pa s
σ = 73×10^{-3} N/m



Large nozzle:

d_c = 320 mm
d_i = 2x44 mm
d = 64 mm
h_c = 22 mm
l/d = 0.15625
α = 60°

Re_W = 2,071
ρ = 1,223 kg/m³
μ = 0.1 Pa s
σ = $62.5\cdot10^{-3}$ N/m

In Fig. 2, typical contours of the axial velocity obtained in the numerical simulations are shown. Regions of higher velocity in the liquid can be found near the air core and at the wall. Interestingly, approximately one half of the total flow passes through these portions of the swirl chamber despite their limited area, being in good agreement with the corresponding experimental observations made by Cooper [6]. The liquid passes the concave wall, giving rise to hydrodynamic instabilities that result in the formation of Görtler vortices. Figure 3 displays a detailed view of one of such Görtler vortices, as visualized by pathlines coloured by the magnitude of the axial velocity. Other secondary flow features, such as nonuniform flow distribution, are also readily visible.

In both nozzles, the interface between the liquid and the gas becomes unsteady, displaying waves of small amplitude along its surface (Figs. 4 and 5). The waves originate at the nozzle top, at the stagnation point on the lid, and propagate toward the exit. Their amplitude seems to decrease with increasing axial distance. After the exit, however, it increases again, causing at times violent movement of the liquid sheet. The stagnation point next to the top lid is found in both nozzle simulations. It leads to the formation of a crest at the nozzle top, which can reach the symmetry axis if the grid resolution is not sufficient. The fluid has now only one possibility to find its way to the orifice. The mutual interaction of the above phenomena at this point results in the formation of unsteady waves. (since the flow has to be deviated downward to the outlet, a vortex forms in the chamber, contributing to the wave formation on the free surface. In the simulation of the large nozzle, a breaking waves appear). Moreover, in the authors opinion, the wave formation phenomenon is sustained by the recirculating air flow in the nozzle (zone of negative velocities in Fig. 2). A Fourier analysis performed of the time signal related to the timewise variation of the lamella thickness at the nozzle exit reveals a fundamental frequency of 8.5 Hz. The corresponding amplitude of the change of the lamella thickness at the orifice was 0.0002 m.

For comparison purposes, the mean spray angle as resulting from the computations was also determined. For the large nozzle, it was 84° − an exactly same value as mesuread. In the case of the small nozzle, the computed spray angle was 99.5°, the experimentally determined spray angle amounted to 100.8° . Again, the agreement can be considered good.

Air core instabilities

An interesting phenomenon has been observed in the present simulations, whereby a localized region of the air core expanded and contracted in a regular periodic movement. The frequency of these contractions increased with increasing flow rate.

One possible explanation, favoured by Cooper [6], is that these instabilities are produced by toroidal vortices rotating about the air core. These vortices may be very much like smoke rings in air with a roughly circular vertical cross section but being of sinusoidal shape in the horizontal plane. They are travelling upstream at the same axial velocity as the fluid flowing downstream thereby appearing to remaining stationary at fixed locations. This theory is very plausible in real three−dimensional pressure swirl atomizers, but does not explain the unsteady waves in the present two−dimensional model configurations.

The second possible explanation is that these contractions are a series of standing waves superimposed on the air core. If the swirl chamber has a natural resonant frequency, then the standing waves would represent minimum and maximum nodes, although it is difficult to see how, at each location, the fluctuations cycle through both a minimum and maximum unless the waves themselves are rotating about the atomizer axis. These phenomena certainly need further investigation; the present authors believe that these cyclic expansions/contractions of the air core are the key to understanding the behaviour of the flow in the exit orifice and in the spray cone and, ultimately, will lead to the explanation of the break−up mechanism of the spray cone into droplets.

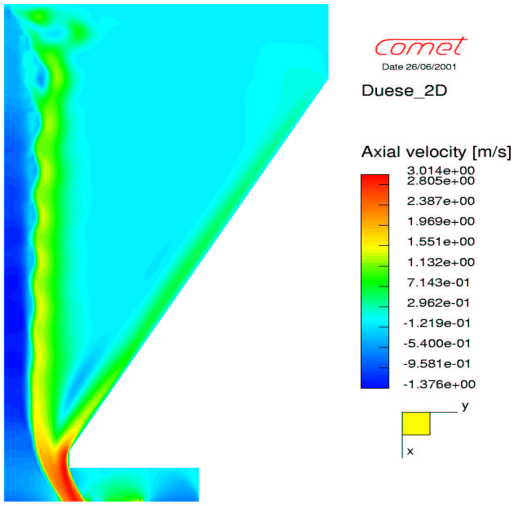


FIGURE 2. Example of instantaneous contours of axial velocity within the large nozzle.

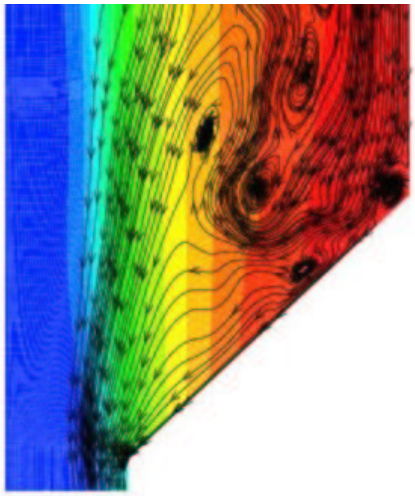


FIGURE 3. Görtler vortices in the swirl chamber of the small nozzle, visualized by pathlines and underlying contours coloured according to the value of static pressure.

Three−dimensional simulations

In most practical cases, the inflowing liquid will be introduced into the swirl chamber by a discrete number of openings, generating periodic asymmetry in the flow field. Therefore, the present authors decided to simulate flow in a three−dimensional configuration as experimentally tested by Cooper and Yule [12]. As shown in Fig. 6, the nozzle has two rectangular inlet ports. The computational grid consisted of approximately 350 thousand grid−cells, giving an adequate resolution in all relevant regions of the nozzle.

The resulting flow was of highly three−dimensional character, clearly visible in the pictures of the air core shown in Fig. 7 a and 7 b. The liquid−gas interface is colored by the air core extension in radial direction. The core was rotating, generating a spiraling disturbance on its surface. Additionally, however, the elliptical crossection was periodically contracting and expending. Both phenomena were observed experimentally by Cooper and Yule [12]. The dominating frequence of these fluctuations was approximately 12 Hertz, being again in good agreement with the experimental data of approximately 12.9 Hz.

It is interesting to note that the critical frequency of the initial liquid sheet aerodynamic break−up, as computed by the simplified linear theory presented by Horvay and Leuckel [10], resulted in 12.5 Hz, being in the same range as the experimentally observed and numerically computed unsteady waves in the swirl chamber.

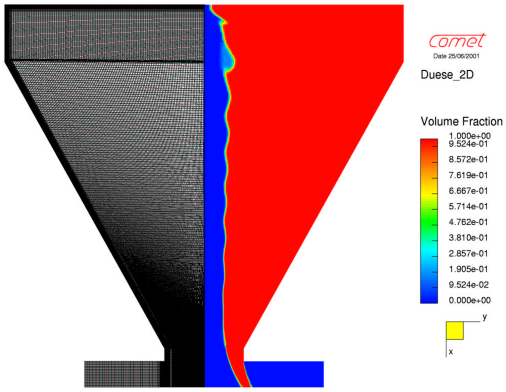


FIGURE 4. Volume fraction distribution for both phases (water−glycerin mixture in red and air in blue) within the computational domain (right) and the corresponding numerical grid (left) for the large nozzle.

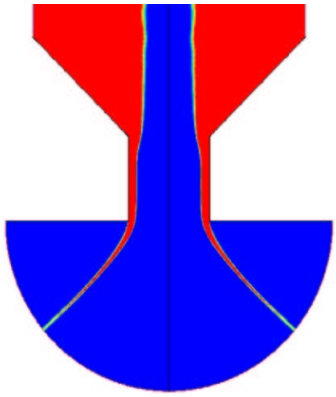
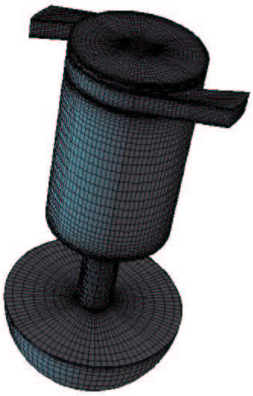


FIGURE 5. Volume fraction distribution within the computational domain (water in red and air in blue) for the small nozzle.



UMIST−nozzle:

d_c = 72.72 mm
d_i = 2x11x12 mm
d = 22 mm
h_c = 11 mm
l/d = 1.815
α = 80°

Re_W = 98300
ρ = 998 kg/m^3
μ = 1.0 10^{-3} Pa s
Re_Y = 152 000 (3−D)
We = 6260

FIGURE 6: Geometrical data for the three−dimensional flow simulations of the Cooper−nozzle.

The qualitative agreement of the experimentally obtained flow visualization data in [12] with the present numerical simulation is obvious. Finally, in Fig. 8, the numerically predicted Görtler vortices are presented. Their location and size are similar to the corner vortex determined in the present two−dimensional simulations and shown in Fig.3. Their presence is indicative of locally laminar flow, being somewhat surprising considering the relatively high Reynolds number. There are indications that the initially turbulent flow relaminarizes after entering the swirl chamber and becomes again turbulent in the exit nozzle (see Fig. 7 a and 7 b).

Conclusions

The flow simulations in a large and a small model nozzles were carried out in the present work using the assumption of either axisymmetric two−dimensional flow or fully three−dimensional flow. For this purpose, two commercially available computer codes were used, **FLUENT** and **COMET**. Both delivered very similar results.

The flow at the air core interface has been shown to be unsteady, with waves generated at the nozzle top end and propagating towards the open end. From spectral analysis, we found out frequency values that are

typical for observations made by [6]. The mean spray angles agreed also well with experimental data. Results obtained by the present two−dimensional simulations are very encouraging, since they enable us to gain understanding of the nature of the nozzle internal flow. The three−dimensional simulations revealed much more detail about the nature of the flow field and are, therefore, obligatory for understanding the flow under investigation, such as the presence of Görtler vortices at the wall or the rotating air core. In the future work, the expected transitional behaviour of the flow will be investigated.

Acknowledgements

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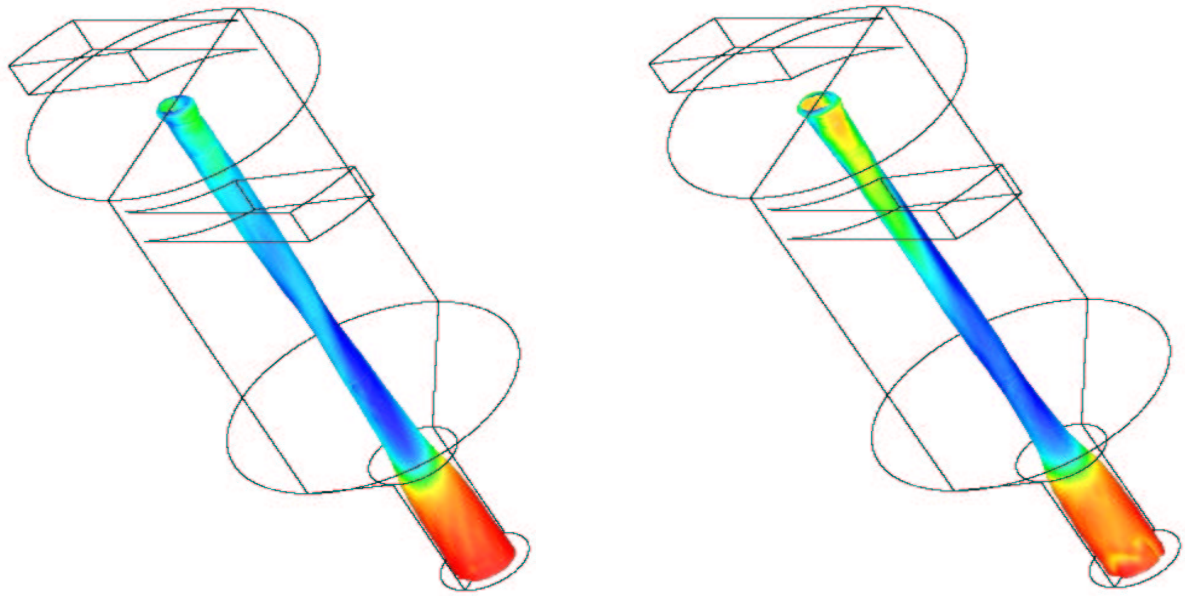

FIGURE 7 a and 7 b: Fluctuations of the air core at two different times.

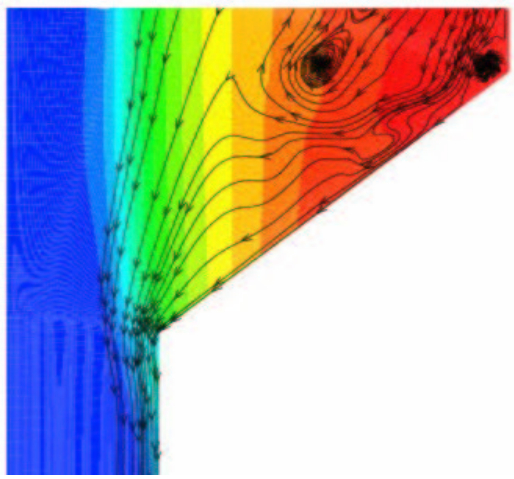

FIGURE 8: Numerically simulated Görtler vortex in the three−dimensional Cooper−nozzle.

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