Three-Dimensional CFD-Simulation of a Thermal Bubble Jet Printhead

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ABSTRACT

This paper reports on a three-dimensional simulation of a commercial, thermally actuated bubble jet printhead using an appropriate pressure boundary condition for the bubble nucleation and expansion. The ink jet system has been used as a realistic show case for the application of the volume of fluid (VOF) method that is implemented in the simulation package ACE+ of CFDRC [1]. Comparing the results obtained by computational fluid dynamics (CFD) simulations with stroboscopic and gravimetric measurements, excellent agreement with experimental findings has been obtained. The differences in ejected droplet volume and droplet speed between simulation and experiment have been lower than 5 %. The simulation tool applied has been used to derive quantitative predictions not only in simplified two-dimensional test geometries, but also for the real three-dimensional device. It proves to be a valuable tool for cost- and time-efficient optimisation of printhead performance.

Keywords: bubble jet printhead, computational fluid dynamics (CFD), volume of fluid (VOF)

1 INTRODUCTION

High quality colour image, low machine cost and low printing noise are basically the main advantages of ink jet printers. This has led to a rapid expansion of this technology in the recent years. The two competing actuation principles of these, so-called drop-on-demand printers are the piezoelectric driven printhead invented in 1972 [2] and the thermally actuated bubble jet printhead developed in 1984 [3]. Currently the bubble jet printer outstands with low manufacturing costs at comparable print quality. The aim of manufacturers and many research establishments is the further optimisation concerning maximum print frequency, active area of the printhead, resolution and quality of ejected droplets. This requires a further miniaturisation and optimisation of the printhead geometry including fluid channels, heaters and nozzles to achieve an ideal printhead performance. An important tool for the optimisation is the simulation of the complete device which is very cost- and time-effective compared to experimental hardware optimisation according to the trial and error principle. With CFD a variety of relevant parameters like geometry effects and ink properties can be investigated.

2 SIMULATION PROCEDURE

Due to the complexity of the ejection process of a thermally actuated bubble jet printer including heating of a micro-heater, bubble nucleation, collapse of the vapour bubble and the actual droplet ejection no complete physical simulation could be accomplished so far. The simulation task is typically divided into smaller sub problems like actuation and ejection. To model the actuation it is necessary to find an appropriate pressure boundary condition to substitute the complicated bubble nucleation, expansion and collapse. Using this as input for the simulation package ACE+ of CFDRC a computational fluid dynamics (CFD) simulation has been set up and the droplet ejection process has been studied. Using a complete three-dimensional model, instead of a simplified two-dimensional one, provides the opportunity to examine the influences occurring only in the three-dimensional case. For instance this can be the effect of asymmetric ink inlet channels or a non-spherical bubble shape. But also the effects appearing at problematic parts of the printhead geometry, for example problems of the capillary refilling at convex edges or transitions between the angular nozzle chamber and the round nozzle, can be examined in 3D simulations. A further advantage of the three-dimensional case is, that the realistic flight path of the droplet can be studied in dependence of the whole geometry.

2.1 Pressure Boundary Condition

Asai et al [4,5] presented a model for the conversion of a given current pulse through a micro-heater of a conventional bubble jet printer into an equivalent pressure pulse using the Clausius-Clapeyron equation.

$$P_v[T_v] = P_{atm}\exp\left[\frac{w\cdot Q_{vap}}{\mathrm{R}}\left(\frac{1}{T_b}-\frac{1}{T_v}\right)\right] \quad (1)$$

Where P_v and T_v are the approximately uniform pressure and temperature in the vapour bubble, P_{atm} is the atmospheric pressure (= 100 kPa), R is the gas constant (= 8.3148 J mol^{-1} K^{-1}), T_b is the boiling point of the ink, and w and Q_{vap} are molecular weight and heat of vaporization, respectively. Adding a time-dependent heating pulse leads to the following exponentially decreasing pressure function $P_v[t]$ which is displayed in figure 1.

$$P_v[t] = P_t(T_t)\exp\left[-\left(\frac{t}{t_0}\right)^{\lambda}\right] + P_s(T_{amb}) \qquad (2)$$

Where $P_t(T_t)$ is the initial bubble pressure depending on the maximum heating temperature T_t. In this case the initial bubble pressure is 9 MPa. P_s is the bubble pressure in the later stage depending on ambient temperature T_{amb}. The parameter t_0 is a time constant, which has been estimated from the bubble dynamics to be 0.17 µs [4,6]. λ is a coefficient, expected to be between 0.5 and 1.5, but should be determined by experimental bubble growth data [4-6]. It was taken to be 0.5.

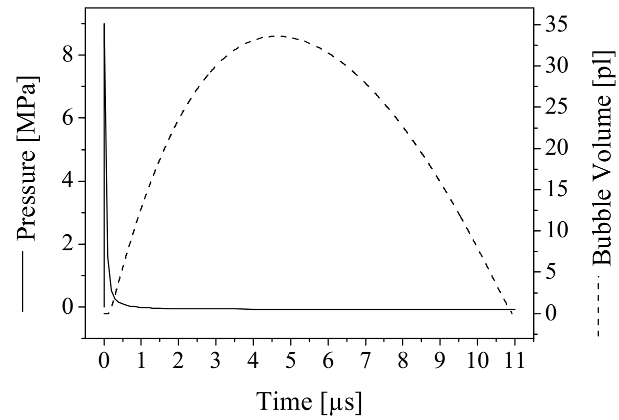

Figure 1: Pressure pulse used as pressure boundary condition calculated by applying the Clausius-Clapeyron equation and the resulting bubble volume.

2.2 Resulting bubble volume

The presented pressure boundary has been applied to the model of a commercial printhead design by substituting the heater area of the real design with an inlet pressure boundary in the simulation using air as incoming medium. The pumped air form the bubble displaces the ink and creates a flow through the nozzle and back into the reservoir. The exponential decreasing pressure function results in a parabolic time-dependency of the bubble volume as displayed also in figure 1. Whereas maximum bubble volume and time range depend on the printhead geometry and ink properties.

This approach and different variants of it have often been used in literature to simulate simple 2D devices [7-9]. Results for such 2D geometries could easily be reproduced using the VOF module including surface tension as implemented in ACE+. Following these initial tests a more complicate 3D model, depicted in figure 2, has been set up to simulate a complete dosage cycle of a printhead developed by the company Olivetti I-Jet [10] including first priming, printing and refilling. Thus it was possible to simulate the print frequency for what otherwise a second tool like a network simulation would have been necessary. The simulation of such a complete ejection process takes about two days of computing time on a state of the art PC.

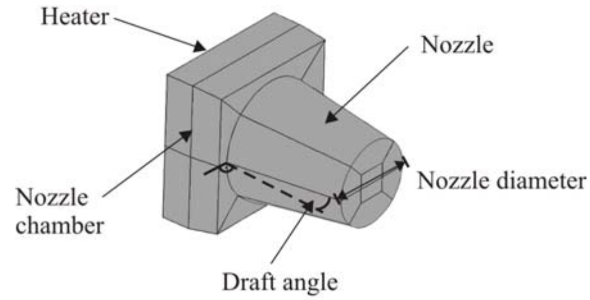

Figure 2: Simplified picture of the 3D model of one nozzle of the bubble jet printhead showing only the fluidic part (inlet channels not shown).

3 SIMULATION VS. EXPERIMENTS

Comparing the simulations with experimental results like stroboscopic pictures as displayed in figure 3, good qualitative agreement has been obtained. The shape of the droplet and the tail look very similar. A detailed look at the simulation output also reveals the non-spherical shape of the bubble, which affects the droplet trajectory. The gravimetrically measured droplet volume of 26 pl agrees very well with the simulated volume of 24.8 pl as well as the measured droplet velocity of 11 m/s, which is extracted from the stroboscopic measurements, agrees with the simulated one of 10.5 m/s. The duration of an ejection cycle of 70 µs in the simulation leads to a theoretical achievable print frequency of about 15 kHz whereas the experiment shows a maximum frequency of about 12 kHz due to the fact that the electronic circuit limits a faster execution. Thus the used pressure boundary condition, presented for the first time by Asai for a 2D case, can also be applied successfully for the 3D case. The applicability of the simulation model is validated with tolerable deviations.

4 SIMULATION RESULTS

After having validated the simulation model further simulations have been performed to optimise the printhead with fixed guidelines by varying parameters like geometry dimensions, heating pulse or ink properties.

4.1 Assembly and packaging tolerances

The determination of the influences of geometrical tolerances on the droplet volume and velocity, are depicted in figure 4. Knowledge of the allowable tolerances is very important for the assembly and packaging of the printhead. Especially the effect of lateral adjustment deviations or differences of chamber height are interesting for the current research project: A new one inch large printhead shall be

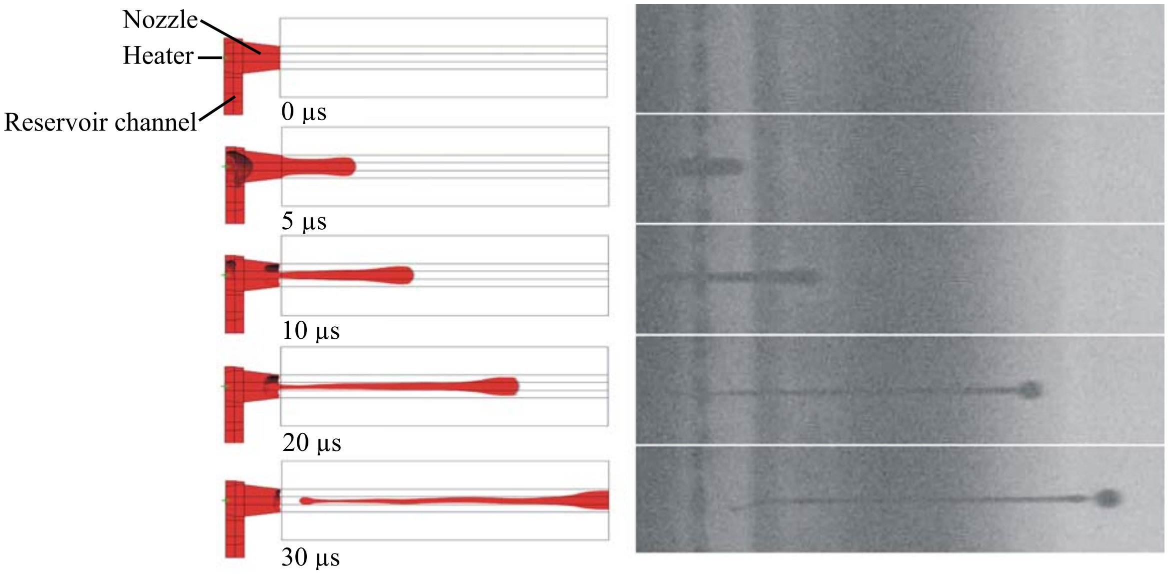

Figure 3: Comparison of the 3D simulations of the droplet ejection (only the fluidic part is shown) and the corresponding stroboscopic pictures.

developed which is a technical challenge for the assembling and packaging. Results of this examinations are, for instance, that a small variation of the nozzle chamber height or a minimal deviation of the adjustment leads to a negligible change of the resulting droplet volume and velocity whereas a deviation of the nozzle diameter or its draft angle induces a more significant change of the ejected droplet volume and velocity as depicted in figure 4.

4.2 Ink properties

It is well known that the ink properties play a major role in determining the print volume. Tuning of the ink is the usual method ink jet manufacturer apply to adjust the volume. Varying the ink parameters like density, surface tension or dynamic viscosity leads to a significant change in the droplet volume as displayed in figure 5. The droplet volume can be halved by increasing the density six fold. But reducing the droplet volume by varying ink parameters induces further changes in the ejection behaviour. The droplet velocity is also very sensitive to fluid properties especially to the ink density (cf. also figure 5). High density ink leads to very low droplet velocities, which is not desirable. Furthermore also altering surface tension or viscosity causes a significant change of the velocity. Another result of the VOF simulation can be educed by surveying the shape of the ejected droplet and its tail. Tail length and potential satellites are an important criterion for

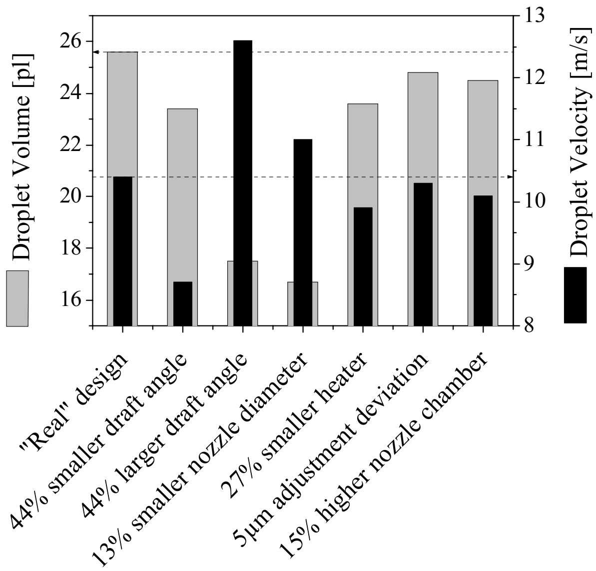

Figure 4: Comparison of simulated droplet volumes considering different geometrical tolerances.

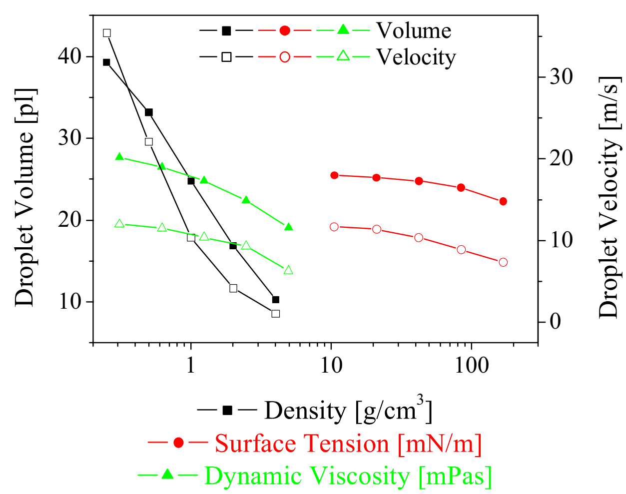

Figure 5: Simulated droplet volume and velocity depending on the density, the surface tension and the dynamic viscosity of the ink, respectively.

the quality of later printouts. The dependence of the tail length on the different ink properties is illustrated in figure 6. The bandwidth of the tail length ranges between very long tails (1000 µm) and very short tails. In a very long tail, the tail breaks in some satellites whereas in very short ones, the tail contracts with the droplet so that no satellites occur. Beyond increasing the print resolution [11] and realizing a monolithic printhead [12,13] preventing satellite droplets is an important part of current research and development activities [8,9].

Admittedly regarding this results one has to keep in mind that the ink properties cannot be tuned independently. In reality density, surface tension and dynamic viscosity are intimately connected. Combining all this simulation results the optimum interaction between print head geometry and ink parameters can be found.

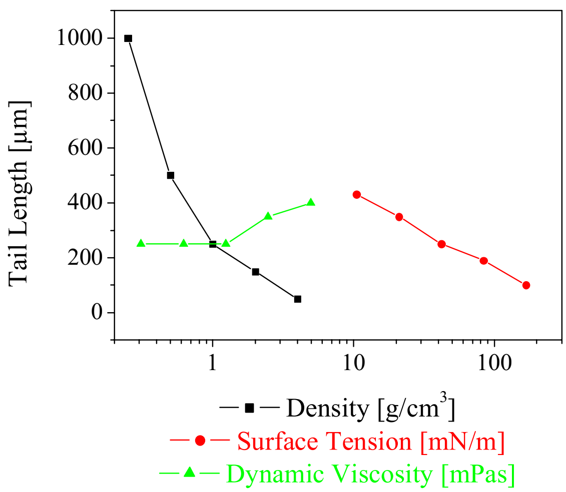

Figure 6: Simulated tail length of the droplet depending on the density, the surface tension and the dynamic viscosity of the ink, respectively.

5 CONCLUSIONS

The presented three-dimensional simulation model of a thermal ink jet printhead provides a valuable approach to optimise thermal bubble jet printheads regarding droplet volume, droplet velocity, droplet quality and print frequency also including the consideration of 3D sensitive problems. The correctness of the used pressure boundary condition and the simulation model in the three-dimensional case was verified by comparing simulation, gravimetrical and stroboscopic results. For the optimisation or the designing of a new printhead a variety of specific models may be investigated by adjusting all relevant parameters like geometry effects and ink properties. Nevertheless it is still inevitable to build prototypes to validate the simulations and to test the functionality. After having established a model CFD is however very helpful to shorten further design cycles significantly.

ACKNOWLEDGEMENT

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