The Simulation of the Viscosity and Surface Tension for the Inkjet Print Head

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Abstract

The simulation of Computational Fluid Dynamics (CFD) is helpful on the development process of thermal inkjet print head. Since the physical scale of bubbles is very small and the manufacturing process is money consuming, it takes engineers a lot of efforts and expenses to do the experiments. A very powerful CFD code as a quick analysis tool is necessary for designing an optimal product. This code must include two models, which are thermal bubble model and free surface tracking model, in order to simulate the printing process. Recently, A great improvement on the CFD code has been achieved.

There are many parameters that influence the flying consistence and direction of the ink droplet. The viscosity and surface tension of ink are two important ones. This research focuses on the effect of the ink viscosity, surface tension and thermal conductivity to the flying behavior of the ink droplet. Four inks are used on this research and compared results with each other. A commercial CFD code is used to simulate the whole inkjet printing process. The 3D model and mesh are first created by a CAD tool and then inputted into the CFD commercial code. The processing time for the simulation is greatly shortened. A formula, which is a function of ink viscosity and surface tension, is generated by the results. The formula describes the relationship between the ink properties and droplet length. An experiment, which set up by research group, using a CCD camera to take pictures on every one microsecond is also preceded. This experimental equipment is a powerful tool for observation of inkjet print head. It includes CCD camera, control board, control program and computer. Comparisons between simulation and experiment results are shown in this paper. The conclusion will be helpful for the development of the inkjet print head.

Introduction

The quality of the inkjet printing is affected by droplet ejection performance. There are many factors affecting the droplet ejection process such as ink properties, microstructure size, operating electronic signal, etc. Chiu et al. (2001) discussed the size effect of the micro channel on the ejection process. He concluded the double-feed-channel model is a better design than the single-feed-channel model. Yang et al. (2002) researched the operating voltage effects on bubble growth dynamics. He proved the larger heat flux rate results in larger bubble pressure and ink velocity using calculation and experimental results. This study is to investigate the effect of ink properties, surface tension and viscosity, on the length of the ejection droplet under the same print head. The new stage droplet observation equipment has been setup. It can show the higher resolution image and automatic size measurement from the image.

The simulation of Computational Fluid Dynamics (CFD) is helpful on the development process of thermal inkjet print head. Since the physical scale of bubbles is very small and the manufacturing process is money consuming, it takes engineers a lot of efforts and expenses to do the experiments. A very powerful CFD code as a quick analysis tool is necessary for designing an optimal product. This code must include two models, which are thermal bubble model and free surface tracking model, in order to simulate the printing process. Recently, Some improvement on the CFD code has been achieved.

The aim of the present study with numerical predictions on the droplet length is to study influence of the surface tension and viscosity of inks and find out the influence factor.

Theoretical Model and Numerical Scheme

Simulation of an inkjet print head is a big challenge in Computation Fluid Dynamics. The size of the structure is quite small, about the order of 10 micrometers, which often causes severe truncation errors in the results. Another challenge is to track the free surface interface between the liquid and gas phase. Free surface interface plays an important role in the simulation because the model requires tracking in a more accurate resolution. CFD was used because the tracking is very complicated and the code has to be capable of capturing the interface accurately.

Volume of Fluid (VOF) method resolves the transient motion of the gas and liquid phase using the Navier-Stokes equations, and accounts for the topology changes of the interface induced by the relative motion between the gas and liquid phase. The VOF method utilizes a finite difference to represent the free surfaces and interfaces that are arbitrarily oriented with respect to the computational grids. The VOF defines a volume fractional function F that indicates the fraction of the computational cell filled with liquid, and uses a donor-acceptor algorithm to track the interface. There exists a free surface interface while the value of F is between zero and unity in a cell. Although VOF can locate the free boundary nearly as well as a distribution of marker particle method and needs less information-stored space, the method is worthless unless an algorithm can be devised for accurately computing the evolution of the F field. The time dependence of F is governed by

$$\frac{\partial F}{\partial t} + F\nabla \bullet \vec{V} = 0\,. \qquad (1)$$

The mass and momentum equations can be written as the conservation form and homogeneous, so

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \vec{V}) = S_c \qquad (2)$$

and

$$\frac{\partial \vec{V}}{\partial t} + (\rho \vec{V} \bullet \nabla)\vec{V} = -\nabla P + \nabla \bullet \tau_{ij} + S_m \qquad (3)$$

where ρ is the density, t is the time, P is the pressure, $\vec{V}$ is the velocity vector, F is the volume fraction function, τ_{ij} is the viscous stress tensor, and S_c, S_m are the source terms.

There are two 3D models, named model A and model B, in the Figure 1. Model A is a double-feed-channel design; Model B is a single-feed-channel design. The main dimensions of the models are listed in Table 1.

Table 1. The main dimension of the models (unit is μm)

	Model A	Model B
Barrier Height	20	30
Nozzle Height	54	50
Nozzle Outlet Diameter	36	39
Nozzle Inlet Diameter	148	135

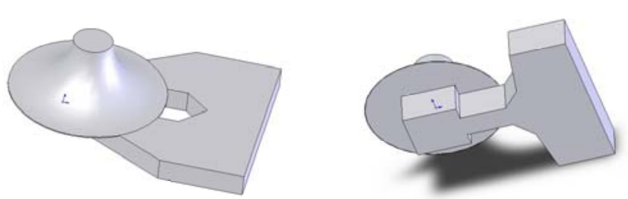

Figure 1. 3D model of Model A and Model B

There are 5 inks used in the present study. The surface tension and viscosity of the inks are listed in Table 2. Only Ink A is used for Model A, others are used for Model B. All inks properties are tested before experiment.

Table 2. Ink properties

Ink	Viscosity (cps)	Surface Tension (dyne/cm)
A	3.29	28.4
B	2.39	31.1
C	2.51	30.6
D	2.17	29.8
E	1.82	28.0

In numerical model, FLOW-3D© is used as the simulation tool. The bubble model that FLOW-3D provided is an advanced bubble in commercial CFD codes. The model describes the bubbles obeying the homogeneous bubble rule, that is, the pressure and temperature of the bubble are spatially uniform. The equation of state (E.O.S.) for a bubble is the ideal gas E.O.S.,

$$p_v = (\gamma - 1)\rho C_V^{vap} T_v \qquad (4)$$

where p_v is the bubble pressure, C_V^{vap} is the specific heat at constant volume of the vapor. γ is the ratio of specific heats for the gas, and T_v is the bubble temperature.

When no heat flux crosses the interface between the heater and ink, phase change begin to occur on the interface of bubble and liquid. It is necessary to have a relation that expresses the saturation pressure of the vapor, P^{sat} in terms of temperature. The common relationship is the Clapeyron-Clausius equation,

$$P^{sat} = PV1 \bullet \exp[-(\frac{1}{T} - \frac{1}{TV1})/TVEXP] \qquad (5)$$

where $PV1$ is saturation pressure of the vapor, $TV1$ is saturation temperature of the vapor, and $TVEXP$ is an exponent constant given by,

$$TVEXP = (\gamma - 1)C_V^{vap} / CLHV1 \qquad (6)$$

where $CLHV1$ is the latent heat of the liquid.

Experiment Equipment

The equipment of droplet observation was setup consist of CCD camera, control board, control program and PC. Figure 2 show the equipment,

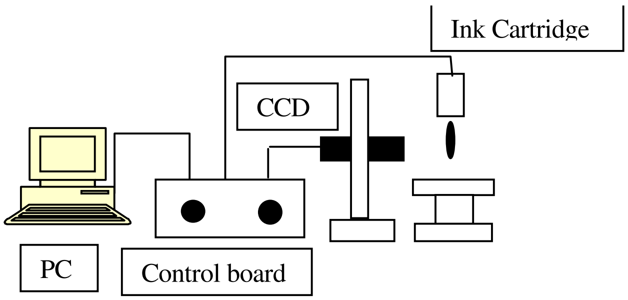

Figure 2. A sketch map of equipment

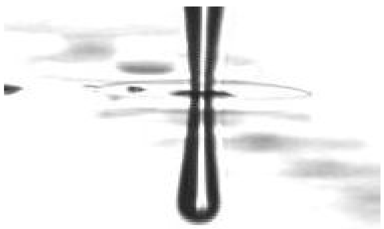

Figure 3. Experiment image

Figure 3 shows the image captured by the experiment equipment. The figure shows the ink ejected out of the nozzle, and its direction is down.

The image postprocessor program was developed by our group to measure the droplet length from the image. The program can measure droplet length on-line and off-line. The program can continually measure the droplet length and output the data to an ASCI text file. Figure 4 shows the image postprocessor program.

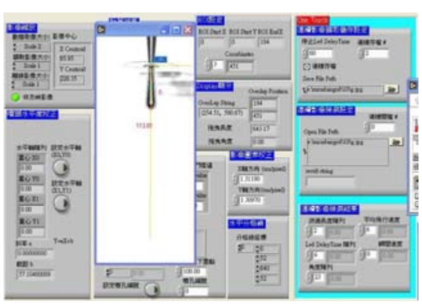

Figure 4. Image postprocessor program

Results and Discussion

The simulation and experiment are doing in the present study. In simulation, the same initial bubble pressure and temperature of the bubble model were setup at each case. There are 5 cases calculated by simulation to compare with experiments. Figure 5 shows the simulation result where 3D model is Model B and ink is Ink B at 6 μ sec. The colors show the pressure contour.

Figure 6 shows the comparison of the droplet length between the simulation and the experiment for the Model A using Ink A. Figure 7 shows the comparison of the droplet velocity which calculated by measured data.

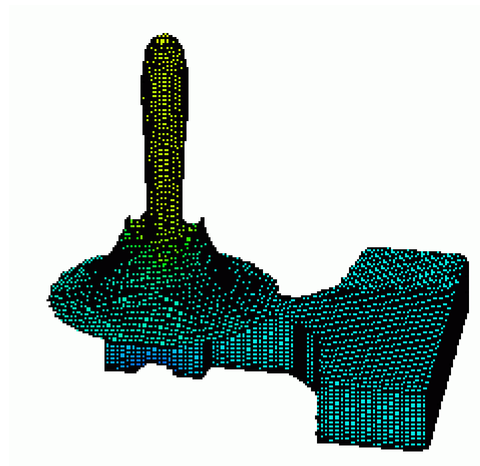

Figure 5. 3D pressure contour of Model B using Ink B at 6 μ sec

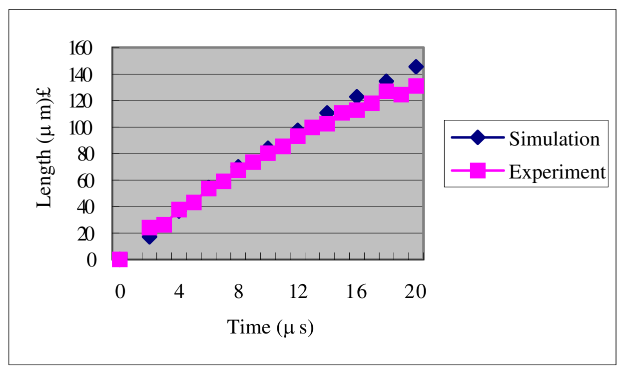

Figure 6. The droplet length comparison between simulation and experiment of Model A

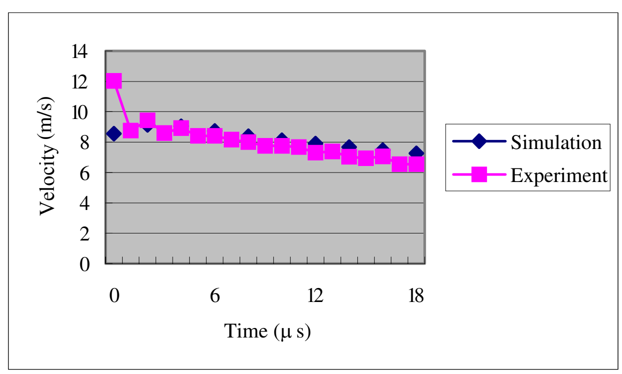

Figure 7. The droplet velocity comparison between simulation and experiment of Model A

The average error between simulation and experiment in Figure 6, 7 are 5.77%, 5.78% respectively except for the 1st image. The image postprocessor program causes first image error. This image is captured by 1 or 2 μsec after firing, when the droplet length is shortest. It is more difficult to calculate the droplet length correctly.

Figure 8 (in next page) shows the comparison of experiment, simulation results and ink properties. The figures show the droplet length from 0 μsec to 20 μsec. From the figure, at the early stage of the droplet ejection, the simulation results are similar with the experimental results. However, at the later stage of the droplet ejection on the comparison of the simulation results, it shows calculating data are closer with each other than the experimental results.

In figure 8, the Ink B has the longest droplet length on Model B. And the surface tension of the Ink B is higher than other 3 inks. It is obvious that the droplet length is concerned with the surface tension of the inks, although the difference is not obvious in the simulation results. No matter what is the results of the simulation or experiment, the sequence of the droplet length at later stage as 20 μsec is the same as that of the surface tension.

In the experimental results, the droplet length of Ink E is different from the numerical result compared with other cases. The reason is that the atmosphere condition of the experimental environments was not under-control.

Conclusion

Since the nucleation process of the inkjet print head is a special, complex procedure compared with pool boil phenomenon. The development of the numerical model is a difficult and hard work. Commercial code may help developer to understand the flow and thermal mechanism. It is not exactly perfect to match the results of experiment.

However, the experiment and simulation can work simultaneously to obtain the similar results. And simulation can sustains work to show the tendency of the ink.

From the present study, the results from the commercial code are shown and compared with the experiment results. There are the same sequences of the droplet length at the later stage of the droplet ejection on simulation and experiment. The average errors of the results of the simulation and experiment are less than 8% except for the case of the Ink E. Surface tension is the mainly factor in the ink ejection process. For numerical model, if it can modify to more match the physics, the well results will be better.

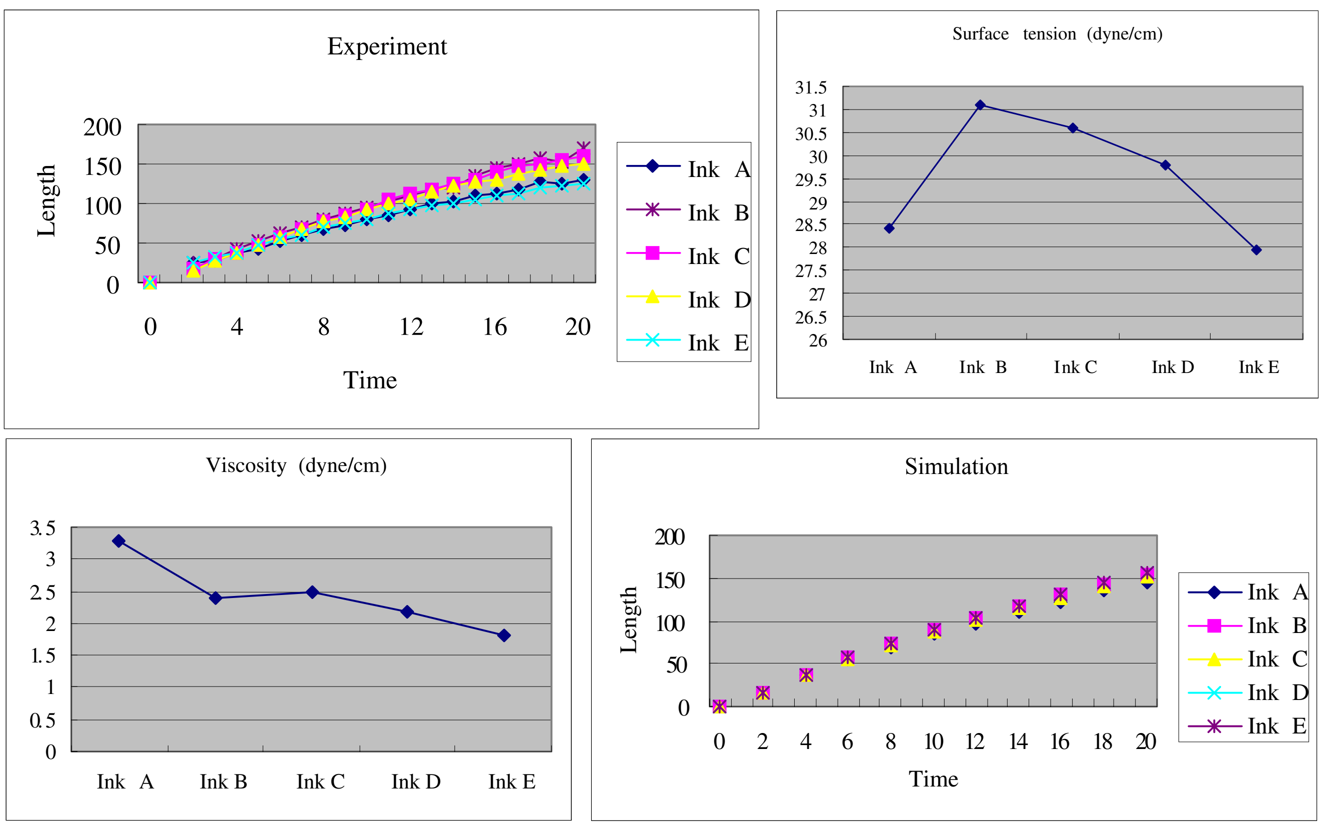

Figure 8. Comparison of the experiment and simulation results and ink properties

References

1. C.L. Chiu, J.C. Yang, C.H. Liu, J.P. Hu, and C.C. Chang, "The Numerical Study on Size Effects of the Inkjet Print Heads," IS&T's NIP18: 2001 International Conference on Digital Printing Technologies, pp.319-322, Fort Lauderdale, Florida, USA (2001).
2. J.C. Yang, C.L. Chiu, and C.C. Chang, "Operating Voltage Effects on Bubble Growth Dynamics of Thermal Inkjet Printheads," IS&T's NIP18: 2002 International Conference on Digital Printing Technologies, pp.153-156, San Diego, California, USA (2002).
3. Flow-3D User's Manuel, V8.1.1, Flow Science Inc. (2003).

Biographies

Ching-Long Chiu joined the Printing Technology Division of OES/ITRI in 1998. He received his M.S. and Ph.D from Institute of Aeronautical and Astronautical Engineering of National Cheng Kung University. His interest lies in the field of computational fluid dynamics.

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