

Master thesis summary

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This document is intended to be a supplementary material that explains my research background and interests. Therefore, most contents are not constructed in a very strict way in order to avoid unnecessary tedious details. However, any discussion will certainly be welcomed if you find anything unclear, confusing or incorrect in this document.

Thesis title: Study of Heat Transfer and Fluid Flow of Bubbles
in a Microchannel

Advisor: Prof. S. Maruyama

1 Background

With the increase of operating frequency and integration of transistors, the power density of CPU is exceeding $10^6 W/m^2$ (as shown in Fig. 1) and reaches the limitation of traditional cooling technique. Innovative cooling technique is demanded to gain higher heat flux removal capability which will improve the performance of CPU and other electronic devices dramatically.

Most of today's cooling devices are utilizing forced convection of air or liquid, while boiling phenomena can evidently offer higher heat transfer coefficient, difficulty in control flow boiling phenomena makes it to be seldom used in the normal electronic product. Additionally, the normal scale boiling is dominated by nucleate boiling and it is known that such cooling technique

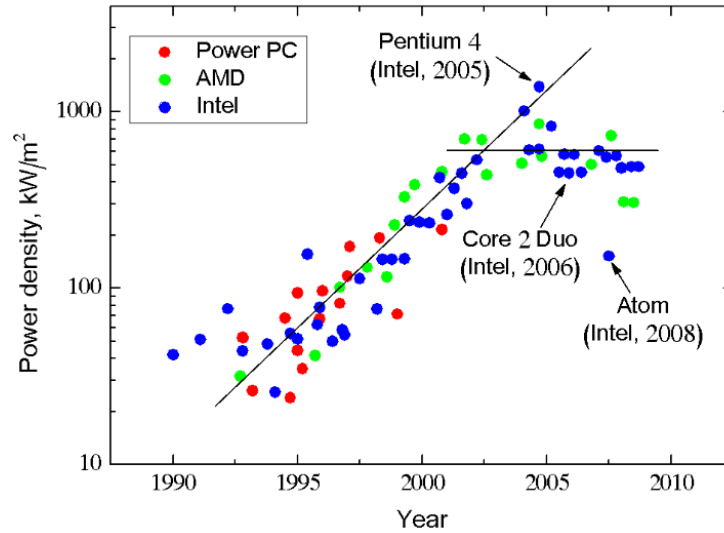


Figure 1 Power density of modern CPU [1].

will fail if the heat flux exceeding critical heat flux is generated from the device surface because of the “dry out” of heat transfer surface.

In order to exceed this barrier and also improve the controllability, a cooling technique utilizing evaporation of liquid film in a microchannel has been proposed by our laboratory (at Tohoku Univ.). In a microchannel, as long as the nucleate boiling is suppressed by controlling channel diameter, expansion of a single bubble and evaporation of liquid film surrounding it will dominate the flow pattern. Although two-phase flow in a microchannel has been extensively studied in the last two decades, research focusing on the film behavior and heat transfer characteristic is far from sufficient and a deeper understanding was needed to develop such cooling devices.

The objectives of this study are to formulate a simulation program and by simulating bubble fluid flow, to understand fluid flow and heat transfer characteristic inside microchannel and help the development of innovative film evaporating cooling technique.

2 My approach for the project

The original plan was to build my own two-phase flow solver from scratch. The reason that we didn't consider a commercial software package (like ANSYS Fluent) or opensource one (OpenFOAM) was:

- Commercial software may lack the flexibility in terms of hackability since the core solver is proprietary and no source code will be available for studying or modifying.
- Available opensource code, for example OpenFOAM, has a massive code base and complex class structure, which may make it too time consuming to study it thoroughly.

As shown in Fig. 2, there would be mainly 3 milestones in this approach:

- Create an incompressible, single-phase, laminar flow solver.
- Implemente interface tracking algorithm (VOF) [2].
- Implemente surface tension model (CSF) [3].

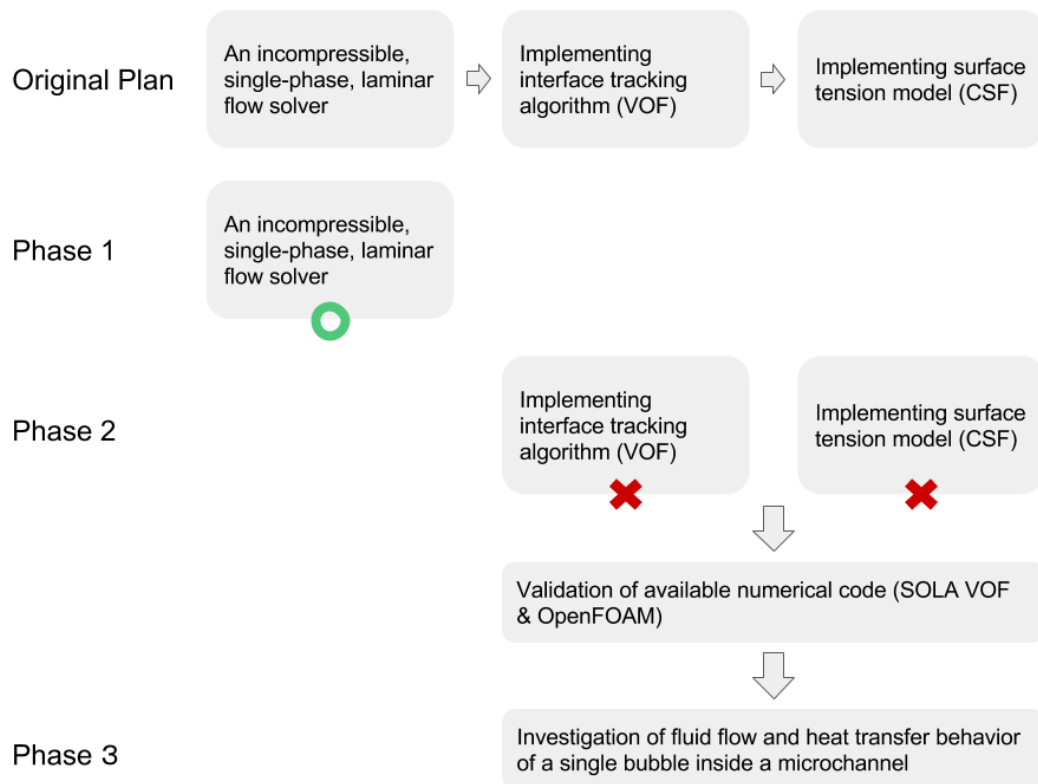


Figure 2 A diagram explaining my master's degree research.

In the first year, a single-phase flow solver (implemented the SIMPLE algorithm [4]), written in Matlab language was successfully developed. However, when I tried to implement the VOF method on top of my code, I noticed that the lack of consideration over program structure and function/class interfaces in my design became a major obstacle that prevent me from developing further complex algorithm.

On the other hand, thoroughly learning through those programming techniques was something I could not afford as a master student. Thus in the second year, I changed the approach from building everything from scratch to utilizing available numerical code.

Results of each phase of my research are described in the following sections.

3 Phase 1: Creating a SIMPLE method simulator in Matlab from scratch

In this phase, a simple solver for single-phase, laminar flow implementing the SIMPLE algorithm was created from scratch (in Matlab). Navier-Stokes equations for incompressible flow are selected to model the problem:

$$\nabla \cdot \vec{v} = 0 \quad (1)$$

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \mu\nabla^2\vec{v} + \rho g + F_b \quad (2)$$

$$\frac{\partial\rho c_p T}{\partial t} + \nabla \cdot (\rho c_p T\vec{v}) = \nabla \cdot \vec{q} \quad (3)$$

Some preliminary simulations were carried out to prove the correctness of this computation code. A typical pipe flow model was built and tested as shown in Fig. 3. The velocity profile on the exit was compared with solution of a typical Hagen-Poiseuille flow case.

I learned extensively about the SIMPLE method and observed how the velocity/pressure boundary conditions are related to each other. It was especially fascinating for me to observe how the order of a matrix (invertible or not) affects the result of the iteration process.

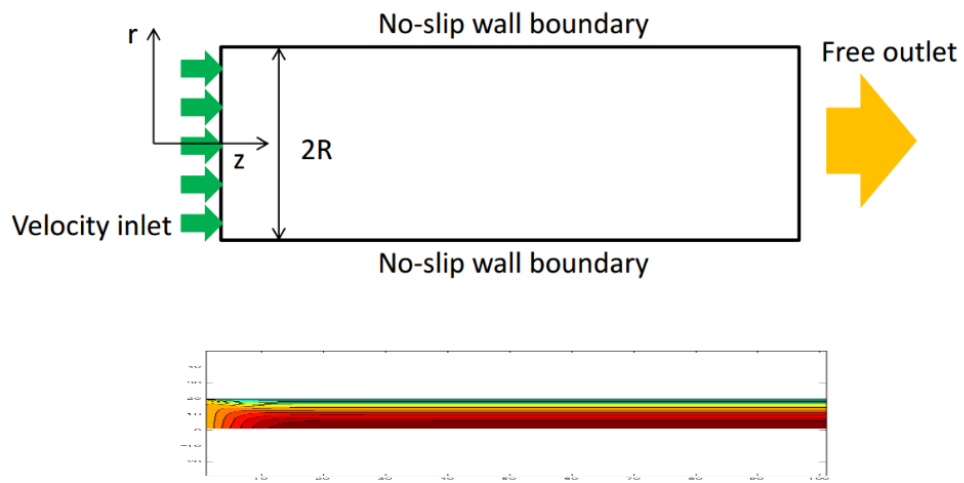


Figure 3 A test case for validation.

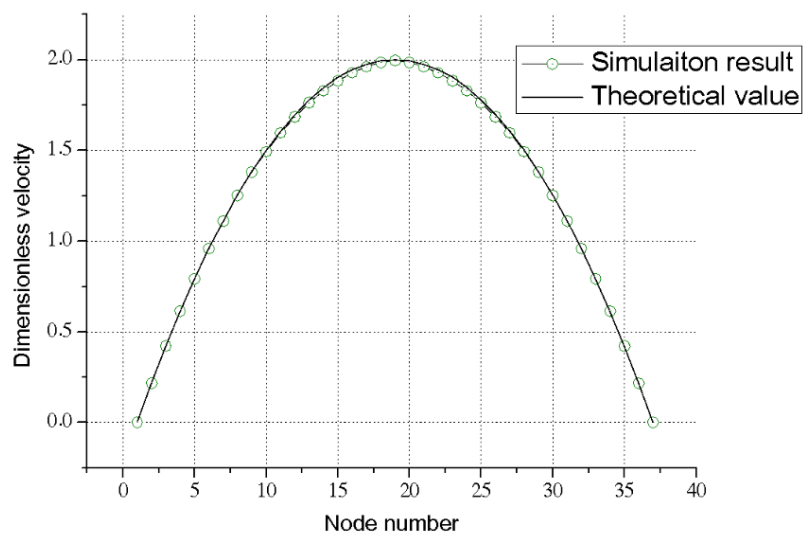


Figure 4 Velocity profile on the exit of pipe flow model.

4 Phase 2: Validation of SOLA-VOF and further results

As described before, in order to obtain reasonable simulation data of two-phase flow, I switched to an available VOF solver called SOLA-VOF (in Fortran language). SOLA-VOF is a numerical solver package for two-phase flow which was originally developed at the Los Alamos National Lab in 1980s [5], and it became available for academical use recently.

To test the ability of the solver, I conducted several numerical experiments including the famous "dam break" (in Fig.5) test case. I also proposed a "steady bubble" test case to test the ability of the solver for micro bubble. (in Fig.6).

In the "dam break" case, the calculated results showed good agreement with experimental data[6].

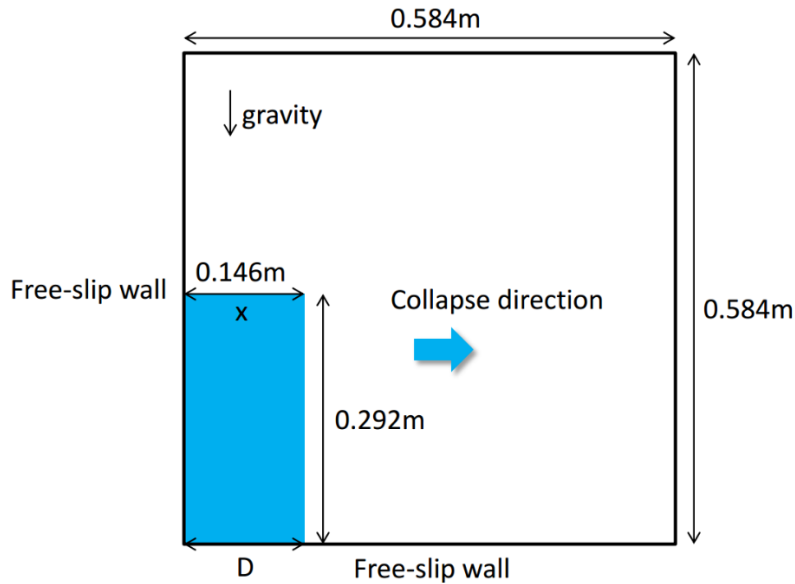


Figure 5 A typical dam break test case.

In the "steady bubble" case, an air bubble is surrounded with water at a resting state. No gravity or other body force is included so it's expected that no velocity in both gas and liquid phase should occur. However, due to the surface tension model utilized in SOLA-VOF has a nature to generate unreal numerical velocity [3], it was found that the interface was under unsta-

ble condition and the original bubble shape would be destroyed under some conditions.

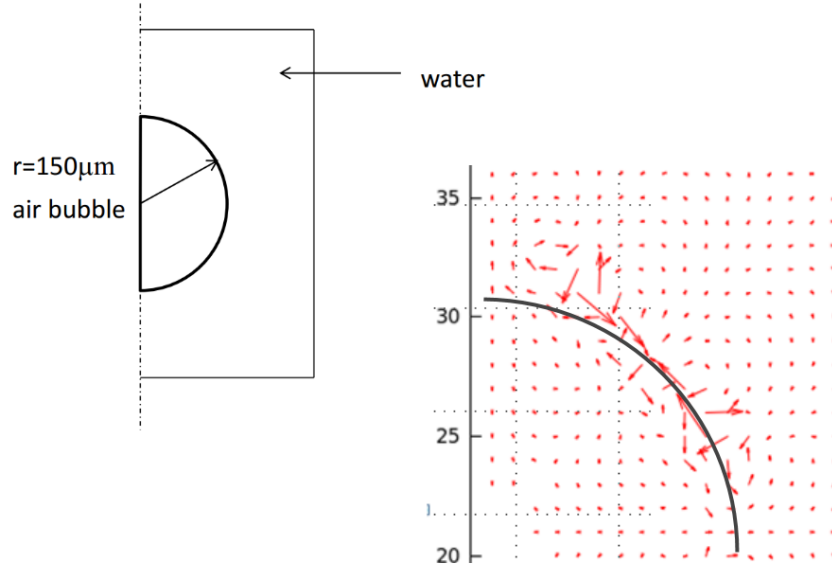


Figure 6 A "steady bubble" test case and the parasitic current velocity observed.

Several numerical experiments were carefully conducted to show the behavior of single bubble inside a microchannel.

Fig.7 shows the physical model and the results. The velocity of gas phase (air) and liquid phase (water) at the inlet is 1 m/s , and the diameter of the channel is $280 \mu\text{m}$. The inlet velocity should be kept above certain value otherwise the parasitic current velocity may dominate the flow pattern and thus the results would be meaningless. It was also noted that due to the lack of grid resolution near the wall boundary, there may occur numerical "dry out" in which the liquid film surrounding the bubble disappear as if the liquid film is evaporated by heat.

The bubble shape was compared with experimental result from other references[7] in Fig.8 and showed good agreement.

As a final step, energy equation was added to the solver to calculate the temperature distribution and heat exchange between the fluid and the wall. It should be mentioned that no phase change model was included and as a result, the bubble could not grow or shrink as what it's expected to behave in reality.

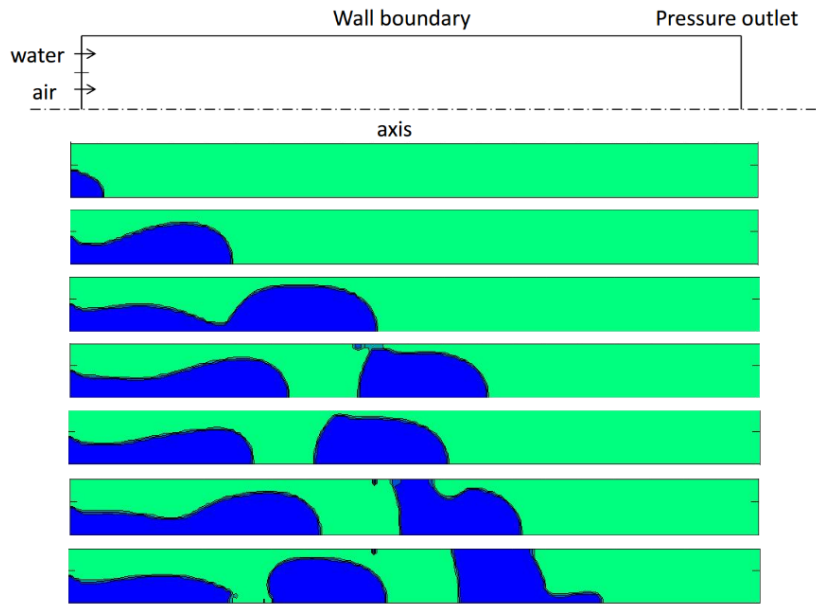
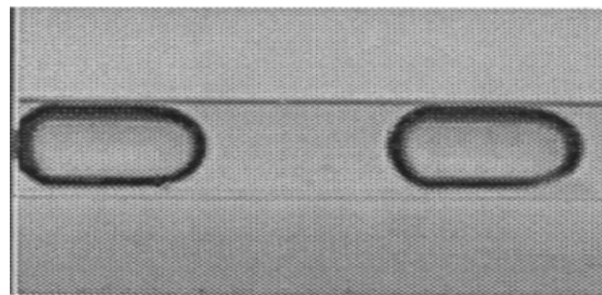


Figure 7 A microchannel model and numerical results showing the bubble shape.



Triplett experimental result



Numerical result in this study

Figure 8 Calculated bubble shape compared with experimental result.

Fig.9 shows that the gas phase temperature was fixed on 100°C and the temperature of overheated water was 105°C . The wall temperature was also fixed to 105°C and thus heat would be absorbed from wall due to the exis-

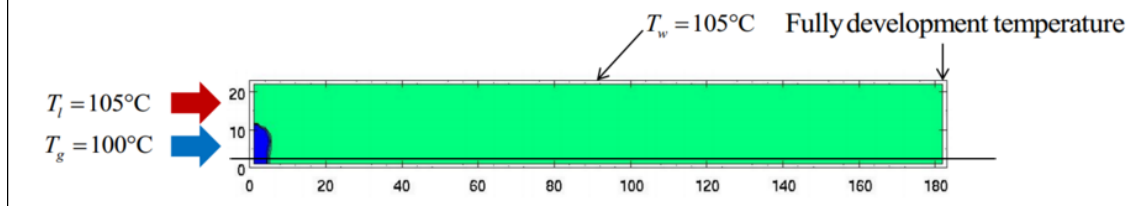


Figure 9 Temperature boundary condition used in this study.

tence of thin liquid film between gas bubble and wall boundary.

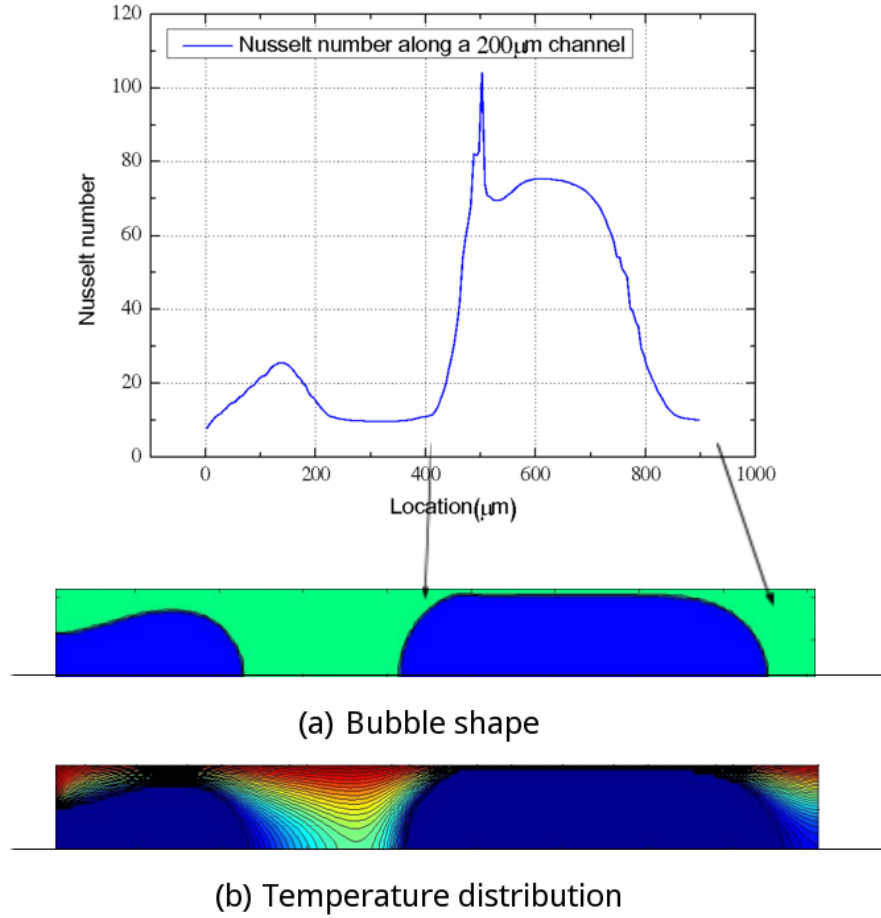


Figure 10 Calculated temperature distribution and derived Nusselt number.

Fig.10 shows the calculated result of Nusselt number along the long-axis of the channel. The Nusselt number was defined as below to reflect the heat exchange rate:

$$Nu = \frac{q_w}{T_w - T_b} \frac{d}{k_L} \quad (4)$$

And T_b is an artificial temperature used to represent the average temperature on a cross section of the channel.

It was found that the existence of liquid film greatly promoted the heat exchange between the fluid and wall, even there was no evaporation effect included in this study. And the spike of Nusselt number on the tail of the bubble suggested that the thickness of liquid film would be a key factor that affect the heat exchange rate.

5 Concluding remarks

The objectives of this study are to formulate a simulation program and by simulating bubble fluid flow, to understand fluid flow and heat transfer characteristic inside microchannel and help the development of innovative film evaporating cooling technique.

In the first phase of this study, I successfully built a single phase laminar flow solver in Matlab. In order to validate the single-phase solver, velocity profile on exit was compared with solution of Hagen-Poiseuille flow in pipe. Results showed good agreement but due to the lack of experience in software development and limitation of time, I decided to change the approach and utilize an available numerical code to continue the study.

In the second phase of this study, I studied the source code of SOLA-VOF method and validated it by conducting several numerical experiments. Although some numerical issues including parasitic current and numerical dry out near wall boundary was found, by carefully setting up the calculation case, a single bubble flow inside a $280\mu m$ microchannel was successfully simulated. Expansion and acceleration of bubble caused by the evaporation of liquid film was neglected to simplify the phase change calculation procedure. Film thickness was found to be extremely important which affects the heat flux directly. Nusselt number and the heat flux result were used to evaluate the cooling ability in current simulation model.

As future work, numerical method to suppress the "parasitic current" will be necessary since the existence of this unreal numerical velocity limited the computable velocity range. Including the evaporation model will make it possible to simulate actual bubble growth and shrink instead of air bubble, which will certainly increase the value of the numerical results and may suggest interesting investigation for further experimental research.

References

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Nomenclature

μ	Dynamic viscosity.
ρ	Fluid density.
\vec{q}	External heat flux.
\vec{v}	Flow velocity vector.
c_p	Specific heat of fluid.
d	Diameter of the microchannel.
F_b	Other body forces.
g	Gravity (vector).
k_L	Heat conduction of the fluid.
Nu	Nusselt number.
p	Pressure.
q_w	Heat flux on the microchannel wall.
T_b	Average temperature on cross section of a microchannel.
T_w	Wall temperature of a microchannel.