おかじま　じゅんのすけ
氏　　　　　名　岡　島　淳　之　介
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（マイクロチャネル内の相変化伝熱現象と生体冷却システムへの応用）
指　導　教　員　東北大学教授　圓山　重直
論文審査委員　主査　東北大学教授　圓山　重直　東北大学教授　大平　勝秀
東北大学教授　山家　智之　東北大学准教授　石本　淳
（加齢医学研究所）　（流体科学研究所）
東北大学講師　小宮　敦樹

# 論文内容要旨

### Chapter 1: General introduction and background

In this chapter, the background of this study is presented. The phase change phenomena and its heat transfer have been used for many kinds application because of the large heat capacity due to the latent heat and maintenance of the saturation temperature during phase change phenomena. The important applications of the phase change phenomena are the cooling of the industrial devices with high heat generation and the refrigeration system to generate low temperature. Especially, boiling phenomenon is essential for these applications.

The boiling heat transfer has been studied so far to develop the safety and efficient cooling in the industrial field. Recently, with the development of the microelectromechanical system (MEMS), the size of device has become smaller year by year. Additionally, a small cooling or refrigeration system has been required to control temperature for small scale in not only industrial but also medical field. In order to satisfy these requirements, the boiling heat transfer in a microchannel has been important.

Previous studies of the boiling heat transfer in a microchannel have concentrated on the heat transfer experiment and finding the precise empirical correlation. Therefore, the phase change phenomenon in a microchannel is not fully understood. In order to develop the high efficient cooling system using a microchannel, following things are important; 1) understanding fundamentals of the phase change heat transfer in a microchannel, 2) development of bubble generation by capillary tube for the stable cooling in a microchannel, and 3) establishment of prediction method of the thermodynamic state of refrigerant in a microchannel.

As the application of phase change heat transfer in medical field, the cooling equipment for cryosurgery, namely cryoprobe is considered. Cryosurgery has succeeded in the treatment of large cancers. On the other hand, downsizing of cryoprobe has been required to extend the application field recently. In order to develop the microchannel cooling system for the biological cooling, important things are 1) evaluation of the cooling performance of microchannel cooling system in the biological tissue, 2) development of an ultrafine cryoprobe and evaluation of its cooling characteristics.

### Chapter 2: Fundamentals of Phase Change Heat Transfer in a Microchannel

In this chapter, a new theoretical model of the phase change heat transfer in a microchannel was proposed based on the liquid film theory. First, conventional liquid film theories were reviewed and validated using experimental data. The bubble expansion model was constructed by the energy balance equation and liquid film correlation. Second, the dominant phase change phenomena in a microchannel were evaluated by using the analytical solution of the wall superheat required to initiate nucleate boiling.

The bubble expansion model was established by using the correlation of liquid film thickness. In addition, the validation of this model was conducted with the experimental data. By comparison between the predicted wall superheat and the wall superheat required to initiate nucleate boiling, the condition of suppression of nucleate boiling was evaluated. Furthermore, the perfect evaporative heat transfer condition under the critical heat flux was investigated. As a result, the boiling limit diameter was derived, as shown in Fig.1. In the microchannel of which diameter is less than the boiling limit diameter, the nucleate boiling is completely suppressed under the critical heat flux.

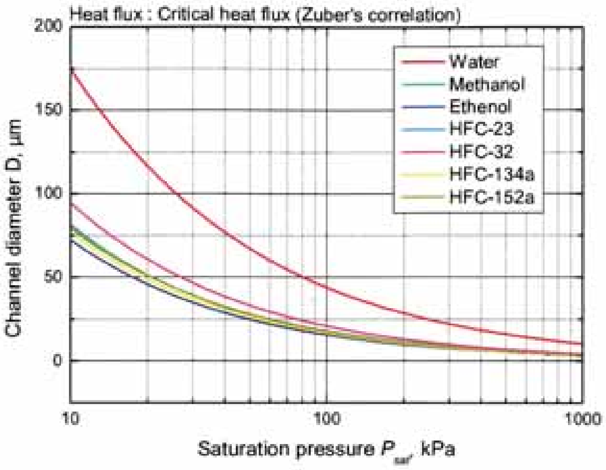

Fig. 1 Boiling limit diameter

## Chapter 3: Bubble Generation by Using Capillary Tube

In this chapter, an experiment of bubble generation by capillary tube was conducted. Additionally, the effect of generated bubble on the phase change heat transfer in a cooling channel was evaluated. Two different sized capillary tubes were made and used as inner tubes of cooling channels. The effect of the difference in diameter of capillary tube was evaluated.

The emission of small bubbles from the inner tube to the glass tube was observed by the visualization experiment. The differences in diameter of inner tube affected the amount of vapor in the outer tube. Moreover, as the diameter of the inner tube became small, low surface temperature of the outer tube was generated due to the low pressure in the outer tube. The relationship between the surface temperature and the heat flux shows that the surface temperature of the thinner inner tube is lower despite the lower mass flow rate.

Additionally, the flow pattern in each channel was completely different during heating the channel. According with this difference, the tendency of wall superheat also differed among each channel. By comparison with the theoretical prediction of the wall superheat for the onset of nucleate boiling, the regime of phase change phenomena was speculated. The heat transfer coefficient indicates that the regime of the phase change heat transfer is different in different-diameter inner tubes. The difference of channel diameter of the inner tube induces the difference of mass flow rate and pressure field in outer tube and also affects the regime of phase change phenomena and heat transfer.

## Chapter 4: Numerical Simulation of Thermodynamic State of Refrigerant

In this chapter, the numerical method was established in order to predict the thermodynamic state and phase change process of refrigerant in a microchannel. The one-dimensional homogenous flow model was selected to calculate the thermodynamic state of refrigerant and several pressure drop correlations were validated. This numerical method was validated with experimental data.

The predicted vapor quality was in well agreement with the experimental data. There were slight differences among the pressure drop correlation. Homogeneous pressure drop model gave well prediction in the low vapor quality region, less than 0.4. In this vapor quality, the effect of bubble dynamics should be small. The results given by classical separated flow model overestimated the pressure drop. It showed the agreement only in the high vapor quality region. This tendency was reasonable because separated flow model based on the theory of annular flow. Pressure drop correlation containing Weber number showed the best agreement. This tendency makes clear because the surface tension affects the two-phase flow in a microchannel.

## Chapter 5: Bioheat Transfer Analysis for the Application of Microchannel Cooling System

In this chapter, the bioheat transfer analysis was conducted in order to evaluate the possibility of cryosurgery by the ultrafine cryoprobe. First, one-dimensional axisymmetric freezing model was solved under the convective heat transfer boundary condition. Dimensionless and dimensional solutions were derived. Second, numerical simulation was conducted using two-dimensional axisymmetric freezing model. The two-dimensional shape of the frozen region and transient variation of frozen region was discussed.

The one-dimensional axisymmetric solutions were validated by comparison with quoted numerical simulation data. The differences between the analytical solutions and the numerical results were acceptable. The relationship among the dimensionless frozen distance, dimensionless heat flux and the dimensionless probe radius was evaluated. Lower surface temperature was required for a smaller cryoprobe to generate the same size of frozen region. In the case of dimensional solutions, when the heat transfer coefficient is $10^4$ W/(m$^2$·K), the temperature difference between cryoprobe of 0.125 mm and 1.5 mm in diameter becomes 20°C. In practical case, this result indicates that it is difficult to maintain the cryoprobe temperature at refrigerant temperature.

Two-dimensional axisymmetric freezing model was solved by numerical simulation. Cryoprobe in the case of minimum cooling power in this condition could not generate the frozen region. The cryoprobe surface temperature in all condition could not reach the refrigerant temperature. The both of refrigerant temperature and heat transfer coefficient affect the frozen region and probe surface temperature strongly.

## Chapter 6: Development of Ultrafine Cryoprobe Utilizing Microchannel Cooling System

In this chapter, the ultrafine cryoprobe for the treatment of small lesion was developed. The basic characteristic of the ultrafine cryoprobe was estimated by the experiment under the insulation condition. Two kinds of cooling methods were compared: phase change and Joule-Thomson cooling. In order to evaluate the refrigerant state inside the ultrafine cryoprobe, the numerical simulation was conducted. Finally, freezing experiments were carried out to check the feasibility of cryosurgery.

The ultrafine cryoprobe cooled by HFC-23 in vapor phase showed the periodic oscillation of surface temperature. This phenomenon was explained by considering the liquid column effect. Furthermore, the cooling power was insufficient to use in cryosurgery. The ultrafine cryoprobe cooled by HFC-23 in liquid phase showed the stability of the surface temperature and the surface temperature was at −50 °C. It is obvious that this cryoprobe has the large heat capacity. Additionally, the heat transfer coefficient of the ultrafine cryoprobe was estimated. The heat transfer coefficient becomes maximum value of 39 kW/(m$^2$·K) at heat flux of 170 kW/m$^2$. Numerical simulation results conducted with the insulation condition showed good agreement with the experimental data. However, the location where the vapor quality becomes more than zero was not predicted well. Moreover, the effect of the heat exchange on the ultrafine cryoprobe was estimated. By using bubble expansion model described in Chapter 2, the regime of phase change heat transfer in the ultrafine cryoprobe was estimated. The results indicate that the nucleate boiling occurs in the ultrafine cryoprobe.

Freezing experiment with agar at 37 °C was conducted. The dependency of frozen region on inserted depth was observed. Phenomena in the case of deeper insertion showed the strong instability and peculiar temperature variation, as shown in Fig. 2. Figure 3 shows the snapshot of frozen region in 180 seconds. This result indicates that non-uniformity of the surface heat flux and temperature affects the phase change state in the ultrafine cryoprobe. At any rate, experimental results indicate that the ultrafine cryoprobe has an enough cooling power to make a frozen region in the living body.

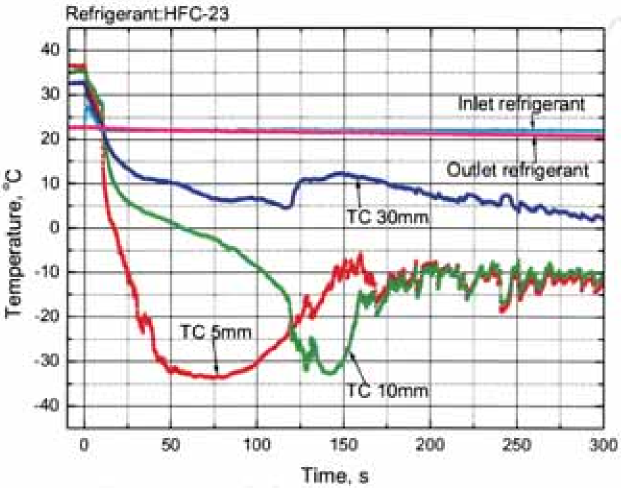

Fig. 2 Time variation of temperature on the surface of ultrafine cryoprobe and refrigerant

Fig. 3 Snapshot of frozen region around ultrafine cryoprobe in 180 seconds

## Chapter 7: Development of Natural Liquid Circulation System

In this chapter, a novel liquid circulation system was proposed. By combined with the ultrafine cryoprobe described in Chapter 6, a refrigeration system with a natural liquid circulation was developed and evaluated. This system worked with the liquid nitrogen to liquefy the HFC-23 vapor. Furthermore, the possibility of a natural liquid circulation system for the electrical devices was discussed. The proposed system will work at room temperature and without the electrical power.

The condenser to liquefy the HFC-23 vapor was developed. It was maintained at −196 ℃ by the liquid nitrogen and the system pressure became lower than the atmospheric pressure. It was clarified that the capacity of the condenser affected the pressure inside the experimental apparatus. When the condenser consisted of one stainless steel tube, the outlet pressure of the ultrafine cryoprobe was more than 0.1 MPa. On the other hand, when the condenser consists of two stainless steel tubes, outlet pressure became less than 0.1 MPa. The cooling performance of the ultrafine cryoprobe of this closed system was same as that of ultrafine cryoprobe explained in Chapter 6. The liquefaction process was succeeded. By using this system, the simulation of actual operation in cryosurgery was conducted. The agar was used as the cooling object. It was clarified that the order of operation of the valves was important to generate a small frozen region and to control the thawing process, as shown in Fig. 4.

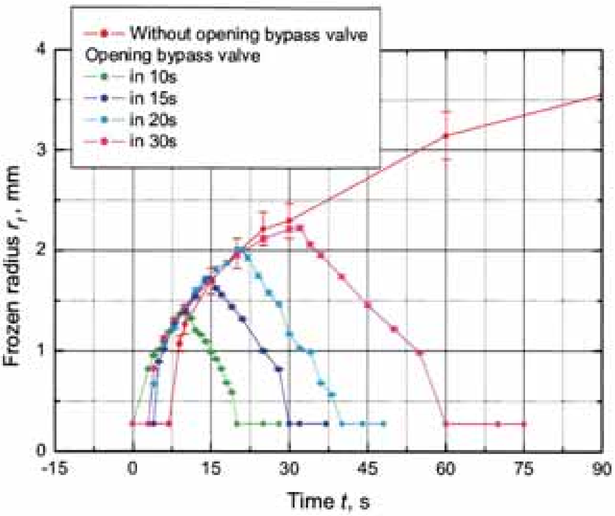

Fig. 4 Time variation of frozen region with controlling bypass valve

## Chapter 8: General conclusions

The founding in this thesis is concluded. In this study, following result and knowledge were obtained.

1. The importance of the time variation of the liquid film thickness was clarified by establishing the bubble expansion model.
2. The bubble emission and flow field after bubble generation can be controlled by changing the diameter of capillary tube of bubble generator.
3. It is analytically clarified that the frozen phenomena by the ultrafine cryoprobe in the biological tissue are strongly affected by the diameter of cryoprobe, refrigerant temperature and heat transfer coefficient.
4. The ultrafine cryoprobe which is utilized the phase change heat transfer in a microchannel has enough cooling power to conduct cryosurgery.
5. By using liquid nitrogen, the room temperature and gravity force, the refrigerant circulation system without the electrical power was established.

# 論文審査結果の要旨

高発熱密度を持つ電子デバイスや1mm以下の病変部などの微小領域の局所冷却は産業界や医療現場など様々な分野で重要である．微小領域の局所冷却を実現するために，マイクロチャネル内の相変化伝熱現象が注目されているが，現象の基礎的な知見やこの現象を利用した応用研究が不足している．そこで，本研究ではマイクロチャネル内の相変化伝熱現象の理論的な理解と医療用デバイスへの応用を行っている．本論文は，これらの研究成果をまとめたものであり，全編8章からなる．

第1章は序論であり，本研究の背景，目的および構成を述べている．

第2章では，マイクロチャネル内の相変化伝熱現象を記述する新たなモデルの提案を行っている．これまで考慮されてこなかった表面張力による液膜厚さの変化を考慮している．これはマイクロチャネル内の相変化伝熱現象の解明へ向けて重要な成果である．

第3章では，毛細管により気泡を生成し，管内に相変化流れを生成する方法について検討を行っている．また，生成された二相流の伝熱特性を検討している．この成果は，マイクロチャネルを利用した冷却デバイスを設計する上で重要な知見である．

第4章では，冷媒の熱力学的状態量の数値計算手法を構築している．マイクロチャネル内での冷媒の局所的な状態変化に着目している．この数値計算法は，マイクロチャネルを利用した冷却デバイスの冷却性能を予測する上で有用である．

第5章では，マイクロチャネル内の相変化伝熱現象を利用した極細クライオプローブの開発へ向けて，微小冷却面による生体組織内の凍結現象を評価している．解析解を用いて一般特性を評価することにより，凍結手術全般において有用な成果を得ている．

第6章では，極細クライオプローブを開発し，その冷却性能を評価している．開発されたクライオプローブは現時点で報告されている中で最も細いものであり，凍結手術の新たな治療分野への応用が期待される．

第7章では，新たな冷媒循環システムを構築し，極細クライオプローブへ応用している．実際の手術方法を検討し，凍結領域の制御手法を提案している．この新たな冷却システムは凍結手術のみならず冷却サイクル開発にも重要な知見である．

第8章は結論である．

以上要するに本論文は，マイクロチャネル内の相変化伝熱現象の解明とそれを利用した新たな医療用デバイスへの応用を行ったものであり，機械システムデザイン工学および医工学分野の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．