Development of Algorithm to Measure Temperatures of Liquid/Gas Phases Using Micro-Thermocouple and Experiment with Optical Chopper

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This paper introduces the algorithm developed to measure the local temperature of phases in the non-isothermal two-phase flow by using micro-thermocouple, which was verified using an optical chopper and a laser. The micro-thermocouple, whose outer diameter of which is 12.7 μm, consists of a couple of alumel-chromel wire (K-type). The hot-junction, a part of the sensor used to for measuring temperature, is fabricated by hot-wire shapes. The response time of the micro-thermocouple, which was measured by dynamic calibration method, was several milliseconds in flow condition. An algorithm to calculate the temperature of each, which is based on the response time of micro-thermocouple and the exponential regression method, was developed. And the developed algorithm was verified through experiments using an optical chopper and a laser.

Key Words : Micro-Thermocouple, Optical Chopper, Algorithm, Exponential Regression Method

Nomenclature

A	: Area (m^2)
Cp	: Specific heat (J/kgK)
h	: Convection heat transfer coefficient (J/m^{2}K)
I, Y	: Coefficient matrix
l	: Width to calculate averaged temperature (sec)
s	: Width to calculate ATD (sec)
t	: Time (sec)
T	: Temperature (℃)
V	: Volume (m^3)

Greek Letters

α, β, γ	: Coefficient
ρ	: Density (kg/m^3)
τ	: Time constant (sec)
Λ	: Coefficient matrix

Subscripts

air	: Air
bubble	: Bubble
threshold	: Threshold
exp	: Experiment
i	: i-th position
J	: Junction

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1. Introduction

To accurately measure quick changes in temperature caused by phase transfer a sensor and an algorithm have been developed. Such measurements had been performed in combustion field by Tanaka and Shimamoto (1979) and the temperature distribution in subcooled boiling had been measured by Jiji & Clark (1964) and Walmet & Staub (1969). Delhaye et al. (1973) proposed that the Probability Density Function (PDF) of temperatures to determine the void fraction in R-114 subcooled boiling using micro-thermocouple. Also, Roy et al. (1991, 1993, 1994, 1995) measured the temperature of liquid and vapor phase using the PDF method.

Recently researches to using a rapid response and a micro-size of micro-thermocouple have been performed. A new experimental technique has been developed for the performance of high temperature, high-strain-rate experiments in the compression Kolsky bar (split-Hopkinson bar or SHPB) pressure using 0.005 inch K-type micro-thermocouple by Lennon and Ramesh (1999). Anders Persson et al. (2004) used 0.13 mm K-type micro-thermocouple to measure surface temperature developing a simplified test method to imitate and evaluate thermal fatigue by deducing the surface strains responsible for failure. A copper-constantan thermocouple of 0.1 mm diameter is used to investigate the fluid flow and local heat transfer around a cube mounted on a wall of a plane by Hajime Nakamura et al. (2001). Liquid temperature was measured using the micro-thermocouple with 0.25 mm diameter by Gopinath Warrier et al. (2002). The applications of general thermocouple to measure surface temperature were widely formed such as researches by Han et al. (2002), Chang and Lee (2003), and Lim and Kim (2004).

Researches for measuring temperatures of phases have been continually performed using micro-thermocouple with a fast time constant. In those researches, PDF method for the statistical analysis of measured temperatures was widely used. However, when the temperature of micro-thermocouple could not reach up to bubble or liquid temperature, it was difficult to obtain an accurate temperature of each phase with the existing simple PDF method.

In this study, an algorithm that can estimate more accurate measurement of the temperatures of each phase using micro-thermocouple in non-isothermal two-phase flow is proposed. This newly proposed algorithm is based on the characteristic temperature curve of micro-thermocouple when temperature change exists.

The lumped energy balance equation can be written as Eq. (1) at the hot-junction of micro-thermocouple assuming that the heat transfer effects of conduction and radiation are neglected since the Biot number is adequately less than 0.1 (Roy et al., 1993).

$$\frac{dT_J}{dt}=\tau(T_J-T_m) \tag{1}$$

Therefore, the lumped temperature equation becomes as follow

$$T_J(t)=T_m+[T_J(0)-T_m]e^{-\frac{t}{\tau}} \tag{2}$$

where $T_J(0)$ means an initial temperature of micro-thermocouple and τ is time constant defined as Eq. (3)

$$\tau=\frac{\rho_J V_J C_{pJ}}{h_m A_J} \tag{3}$$

Also ρ_J, V_J and C_{pJ} are the density, volume and specific heat of the junction respectively. A_J is the junction surface area exposed to the fluid and surroundings and h_m is the convection heat transfer coefficient at the junction with respect to the medium passing the junction. The characteristic curve has the exponential form dependent on time constant as shown in Eq. (3). Therefore, temperatures of surroundings passing the junction such as air bubble and water can be measured using this characteristic of heat transfer at the junction.

The objective of this study is to develop the algorithm to be able to estimate more accurate phase temperature using the self-designed and fabricated micro-thermocouple (12.7 μm, K-type). Also, we verified the performance of the developed algorithm through an experiment with an optical chopper.

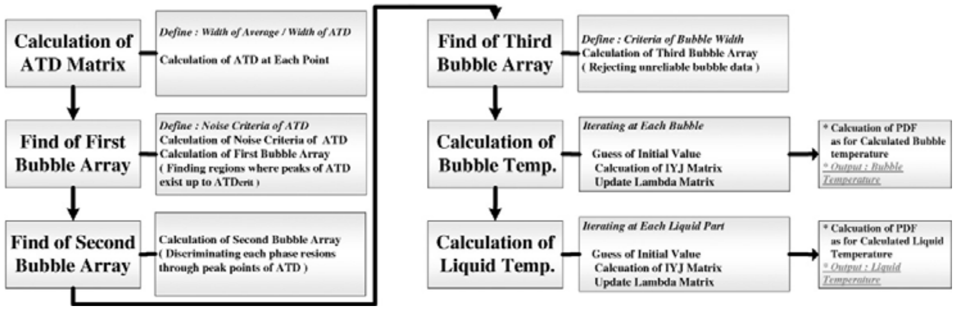


Fig. 1 Flow chart of the developed algorithm

2. Developed Algorithm

The main processes of the algorithm are composed of two steps. The first step is discriminating the phases and the second step is estimating the temperatures of phases. The main process of the developed algorithm is shown in Fig. 1. Each procedure will be explained in this section.

2.1 Discrimination of phases

The first step of the developed algorithm is distinguishing the phase of vapor from that of liquid in raw data of micro-thermocouple in order to find characteristic temperature curve piece by piece. The variation of temperature at the hot junction is started at the moment when the hot junction comes in contacts with other phase assuming that the wetting effects of micro-thermocouple are neglected. Then, the temperature gradient has a maximum or minimum value at the time-position when the medium at the hot junction is changed. That is, at the moment when the change of the hot junction temperature is started or ended. Taking into consideration the effects of noise and fluctuation, the averaged temperature displacement (ATD) of the temperature change can be defined and calculated at each time point, $i+s/2$, as follows,

$$ATD_{i+\frac{S}{2}}=\frac{\sum_{k=(i+S)}^{k=(i+S)+L} T_k-\sum_{k=i}^{k=i+L} T_k}{L} \tag{4}$$

where, S means the time distance between two averaged time-positions to determine the ATD of temperature change and L means the interval of

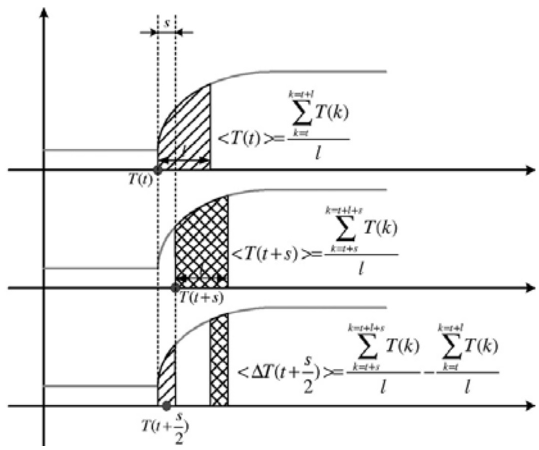


Fig. 2 Concept of the ATD calculation

being averaging temperature at the each time-position. These two parameters are introduced to reduce noise effects of an actual micro-thermocouple signal. Figure 2 shows the meanings of L and S, and Fig. 3 shows the results of the calculation of the ATD as for simulating signal when a single bubble of 100℃ passes the junction in water of a temperature of 90℃ for 30 msec at $t=20$ msec, ideally. The value of S is introduced to average temperature at the short time interval considering the noised and fluctuated temperature signal. The absolute magnitude of the ATD is decreased and the width of the ATD is wide as the value of L increases, therefore the ATD has an advantage of the smooth shape but the distinction with an untrue ATD generated by noises becomes difficult. The absolute magnitude of the ATD is decreased as the value of decreases, also. That is, the magnitude of the solid line ($L=100$, $S=10$) is smaller than the case of the dash-doted

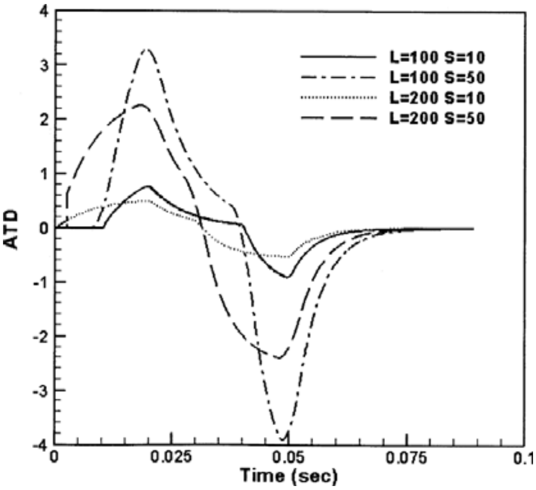


Fig. 3 Sensitivity analysis of ATD parameters

line (L=100, S=50) at Fig. 3.

Besides, the value of L is related to a minimal size for the micro-thermocouple to detect the bubble. Thus, L must be determined to be smaller than the residence time of a minimal bubble. The ATD has a maximum value at time when the bubble starts to pass through the junction and a minimum value at time when the bubble passes through the junction completely in case of single bubble region. Those time positions are not changed even though the value of S and L are changed.

However, the maximum or minimum point of the ATD can be calculated at an untrue position, that is, where the hot junction temperature remains unchanged, due to the noised signal and the fluctuation of medium. Thus, the threshold level of the ATD ($ATD_{threshold}$) is needed to consider the exception of the untrue values. This value is proportional to S and inversely proportional to L. So, it can be determined in the following manner

$$ATD_{threshold} = C_{\exp}\frac{S}{L} \tag{5}$$

where, $C_{\exp}$ is a correct constant to be found experimentally, which is dependent on the characteristics of data acquisition system, namely, noised signal processing and sampling rates. It is determined to have a value of difference between a maximal and minimal temperature signal at the steady state temperature condition.

This ATD, primary information of phases, includes the time region containing areas where extreme value of the ATD exist satisfying threshold level of the ATD, simultaneously. In the next step, the start time position and the end time position of phase changes at the junction should be determined. However, the micro-thermocouple may not have enough time to detect the temperature change if the distance between bubbles is too short.

That is, the information of bubble may be rejected by the ATD threshold, which has been described in the previous step. Since this can happen to errors of measured temperatures, the backward and forward searching procedures need to be considered in order to find the blind information of bubble under the ATD threshold. It is possible that in the ATD information determined by the ATD threshold can, the start position of $n+1$-th bubble positioned at the end position of n-th bubble as shown in Fig. 4(a). This is possible because the magnitude of the ATD at the end position of n-th bubble is less than $ATD_{threshold}$. Two cases can be possible as shown in Fig. 4(a).

The first case is for the end position of n-th bubble to be positioned at the negative ATD region passing through 0 ATD value as the left figure in Fig. 4(a). Then, the end position of n-th bubble is determined to be a position where the ATD becomes zero as forward searching. The second case is that the ATD does not pass through 0 ATD value as the right figure in Fig. 4(a). The end position of n-th bubble is determined to be a position where the ATD becomes a minimum between a start position of n-th bubble and a start position of $n+1$-th bubble as forward searching, also. Thus, the end position of n-th bubble can be found as forward searching from start position of n-th bubble.

On the contrary, the start position of $n+1$-th bubble can be found as backward searching from the end position of $n+1$-th bubble. This case can have two cases with similarity in forward searching procedures. These procedures are shown as Fig. 4(b).

As the final step of discrimination of each phase section, the bubble width criterion is applied to

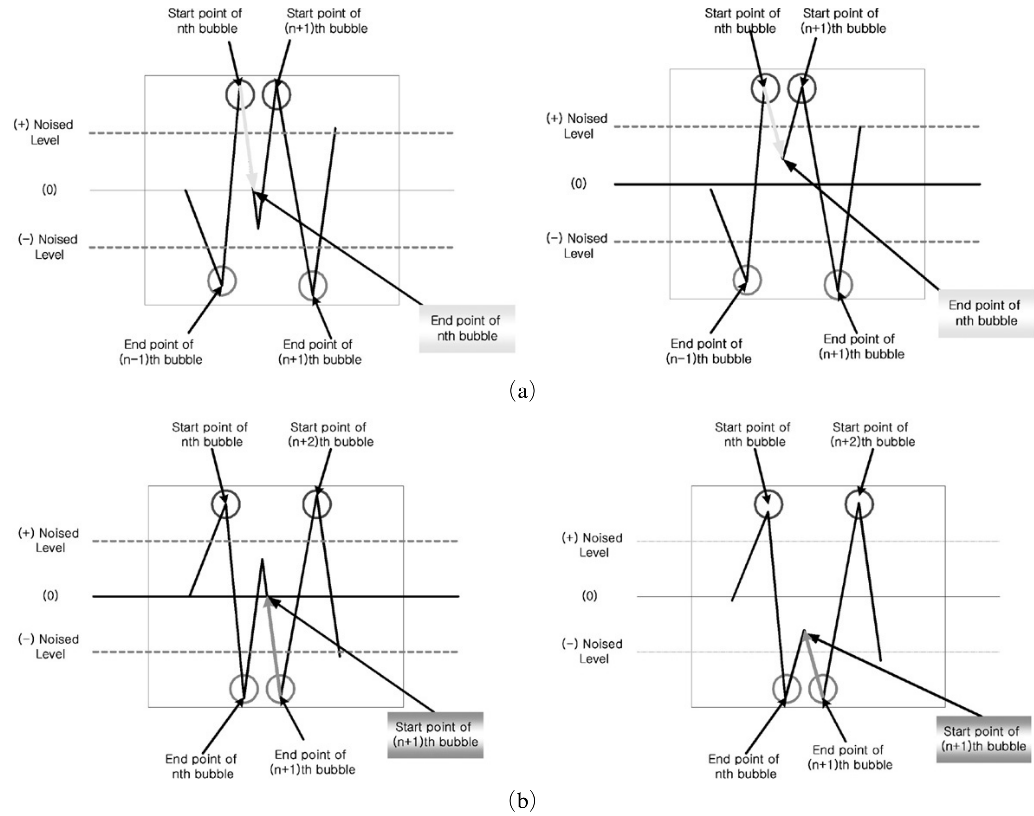


Fig. 4 Procedures to find blind information of bubble (a) Forward searching procedures, (b) Backward searching procedures

information, which successfully satisfies above sequences. The bubble width criterion condition is to remove the non-physical data for bubble residence time, which can be calculated by the noised signal and the averaging process.

2.2 Finding of phase temperature

Bubble temperature is determined based on the characteristics of thermocouple's temperature change and information of discriminating phases in the previous section. It is assumed that temperature change is formed along the exponential curve as mentioned in Eq. (2), so it can be rewritten as follow

$$T(t) = \alpha + \beta e^{\gamma t} \qquad (6)$$

where T is the temperature at the junction. α and β mean $T_{\max}(=T_{bubble})$, $T_{\max}-T_{\min}(=T_{bubble}-T_{water})$, respectively, in time when the temperature is increased by heated bubble, relatively. Those variables are T_{water}, $T_{water}-T_{bubble}$ respectively when the hot junction of the micro-thermocouple is decreased by cold water relatively. $-1/\gamma$ is the time constant of the micro-thermocouple.

If the residence time in the hot junction of the micro-thermocouple is smaller than the time constant or has a magnitude of similar orders, hot-junction will not reach the saturated temperature, which may be the actual bubble temperature or water temperature. So, temperature data is just a part of the whole of exponential curve. In other words, the saturated temperature can be determined by exponential regression method, which was proposed by Langer (1997). The applied procedures of exponential regression can be summarized as follow.

Let y_i and $S(a, b, c)$ be given as

$$y_i = \alpha + \beta e^{\gamma x_i} \qquad (7)$$

$$S(a,b,c)=\sum_{i=1}^{n}[y_i-(a+be^{cx_i})]^2 \qquad (8)$$

where y_i are measured values that have exponential function form at x_i and $a+be^{cx_i}$ is regressed function to find. Therefore $S(a,b,c)$ means residual between measured values and regressed values. Neglecting high order terms of Taylor expansion as for c and each variable at x_i, Eq. (8) can be expressed as

$$\Lambda=I^{-1}Y \qquad (9)$$

where each matrix is defined as followings,

$$\Lambda=\begin{pmatrix} a(c_0) \\ b(c_0) \\ b(c_0)\Delta c_0 \end{pmatrix} \qquad (10)$$

$$Y=\begin{pmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} y_i e^{c_0 x_i} \\ \sum_{i=1}^{n} x_i y_i e^{c_0 x_i} \end{pmatrix} \qquad (11)$$

$$I=\begin{pmatrix} n & \sum_{i=1}^{n} e^{cx_i} & \sum_{i=1}^{n} x_i e^{cx_i} \\ \sum_{i=1}^{n} e^{cx_i} & \sum_{i=1}^{n} e^{2cx_i} & \sum_{i=1}^{n} x_i e^{2cx_i} \\ \sum_{i=1}^{n} x_i e^{cx_i} & \sum_{i=1}^{n} x_i e^{2cx_i} & \sum_{i=1}^{n} x_i^2 e^{cx_i} \end{pmatrix} \qquad (12)$$

The coefficients of Eq. (10) are updated by the repeating calculation after guessing the initial values, and then, calculating the temperatures of phases. Finally, each calculated temperature becomes to build probabilities of temperature and to form PDF.

3. Experiments

3.1 Fabrication of micro-thermocouple

The micro-thermocouple with an outer diameter of 12.7 μm is shaped like a hot-wire in Fig. 5. The micro-thermocouple is fabricated with a couple of alumel-chromel wire (K-type),

The hot junction is twisted and the each wire is electrically insulated by ceramic tube. Each wire is then supported by needle in the fluctuation of water and bubble. The wire with an outer diameter of 12.7 μm is extended with the read wire of 127 μm O.D. by pressing in the needle and by sealing up an epoxy. Each wire adjacent to the junction in the needle is fixed with an epoxy.

3.2 Dynamic calibration

The dynamic calibration of the fabricated micro-thermocouple is performed using Argon-Ion laser beam and shutter as shown in Fig. 6. The aim of this calibration is to find the time constant of the micro-thermocouple, which decides the response time of the micro-thermocouple. And the time constant is used to determine an optical chopper frequency in experiments to verify the developed algorithm.

The measurements are implemented with ranging the flow condition of water and the laser power, 0 to 1.2 m/s and 3 W to 9 W, respectively. The change of laser power means the adjustment of the sudden differences of temperature at the hot junction. The beam is intercepted using the

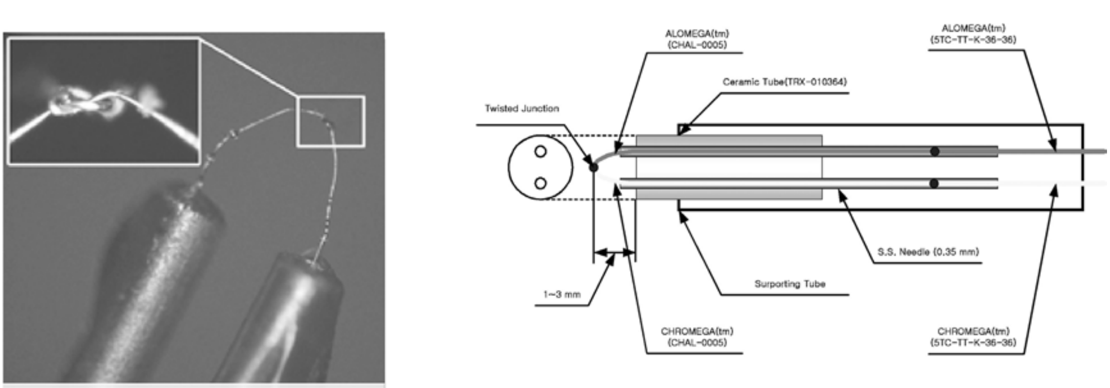


Fig. 5 Self designed and fabricated micro-thermocouple

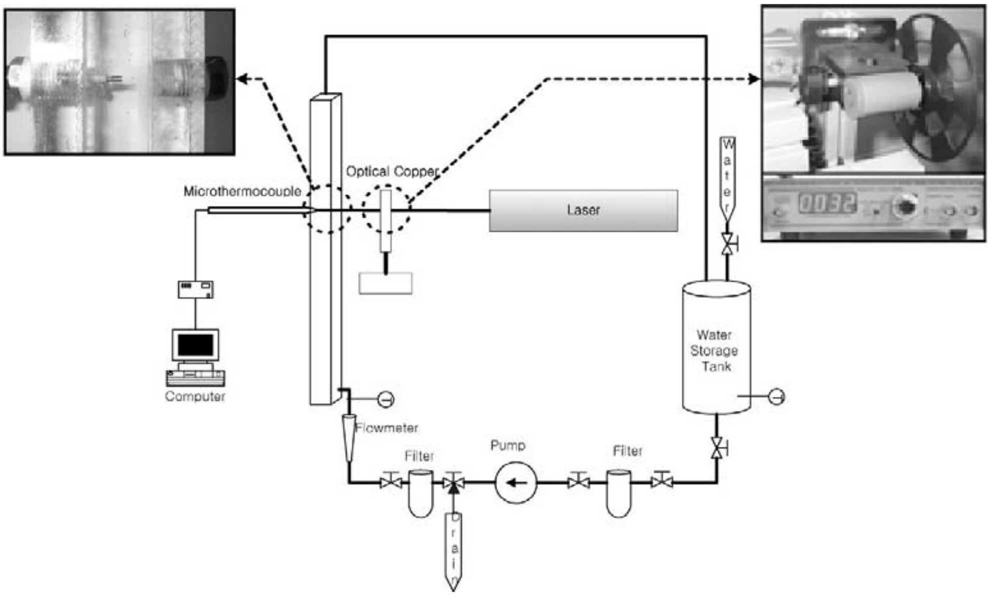


Fig. 6 Schematic diagram of experimental facility

shutter and measurements are conducted when the shutter is open and closed, respectively. The temperatures are obtained by A/D board (DT3003-PGL) during 2 seconds as 300 kHz of sampling rates.

3.3 Optical chopper experiments

By conducting various experiments using optical chopper (STANFORD RESEARCH SYSTEMS, INC. Model SR540), the developed algorithm was verified. Figure 6 shows the configuration of experimental facility using the optical chopper. The experiments were conducted with changing the liquid velocity and the frequency of optical chopper. Table 1, which is determined by dynamic calibration, shows the experimental cases changing optical chopper frequency. The optical chopper has a role of intercepting the heat source from laser. Therefore, the more micro-thermocouple undergoes a thermal variation as adjustment of the frequency of the optical chopper. It corresponds to the bubble when the optical chopper is open and to the relatively cold liquid phase when the optical chopper is closed in case of the subcooled boiling. The frequency of the optical chopper means heating or cooling time at the hot junction. That is, it means the residence time at the hot junction, so the residence time becomes 1.953 msec when the frequency of the optical chopper is 256 Hz as shown Table 1. The steady temperature is measured before and after operating the optical chopper, so minimal and maximal temperatures are measured and are time-averaged separately in each case. Those values are referenced to be transformed temperature into PDF with and without the developed algorithm.

Table 1 Experimental cases

Experiments	Frequency of optical chopper (Hz)	Residence time (msec)
Case 1	32	15.625
Case 2	64	7.813
Case 3	128	3.906
Case 4	256	1.953

4. Results

Figures 7 and 8 show the results of the dynamic calibration. Figure 7 shows the time constant distribution when the hot-junction is exposed to the laser beam by sudden shutter-open and Fig. 8 shows when the shutter suddenly intercepts the laser beam. The fabricated micro-thermocouple has a time constant about 2∼4 msec except that the water is in the stationary state. This means that the fabricated micro-thermocouple can measure bubble and liquid temperature when residence times of each phase at the junction become several milliseconds. Also, results show that the time constant has a similar value, which is independent on the laser power, that is, the time constant is almost unchanged by the difference of temperature of phases.

Figure 9 shows the measured temperature and different phase regime distinguished by the developed algorithm. The left and right-shaded region show the part of heated section by laser and the part of cooled section by liquid, respectively, for raw data of temperature. That is, the shaded regions in the left of Fig. 9 mean each region that temperature is increased by the heat source. After the optical chopper intercepts the heat source, the decreased temperature parts by liquid are expressed as the shaded regions in the right of Fig. 9. The

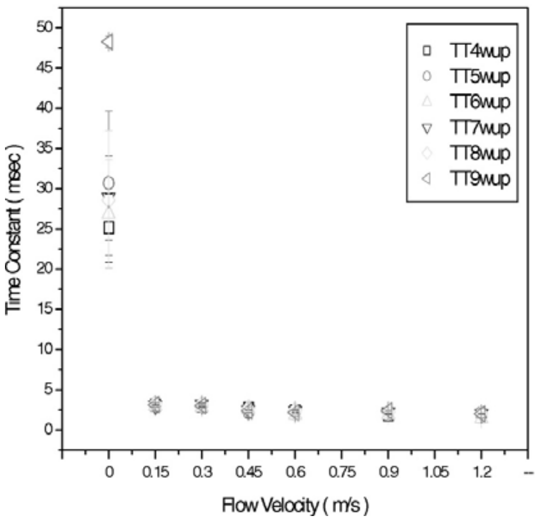


Fig. 7 Time constants with various flow velocity (Laser off-on step)

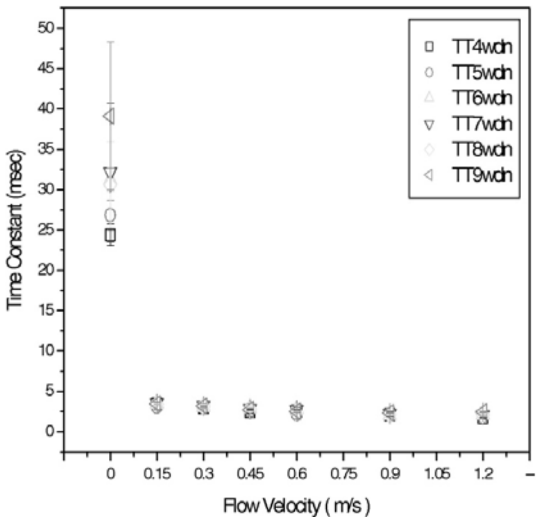


Fig. 8 Time constants with various flow velocity (Laser on-off step)

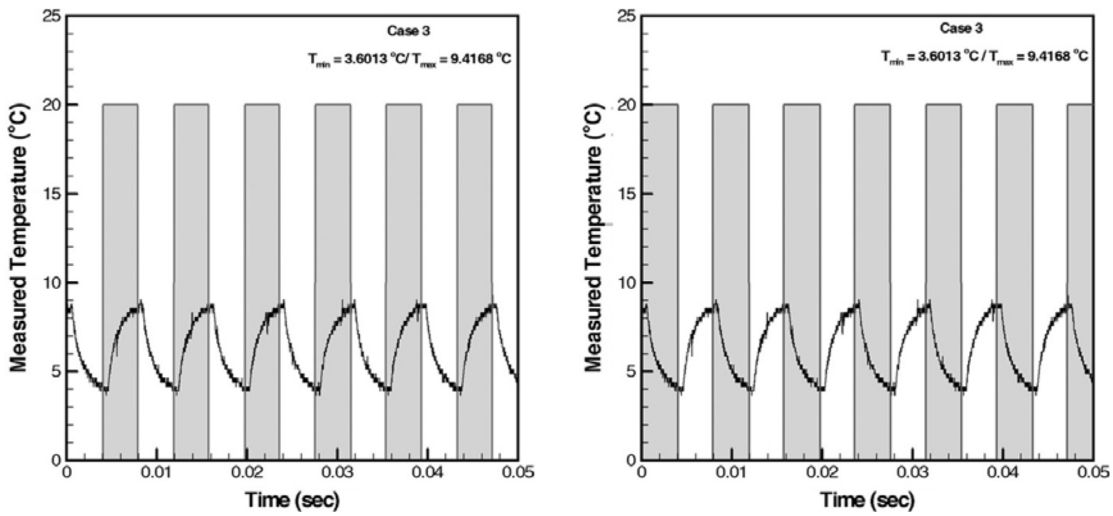
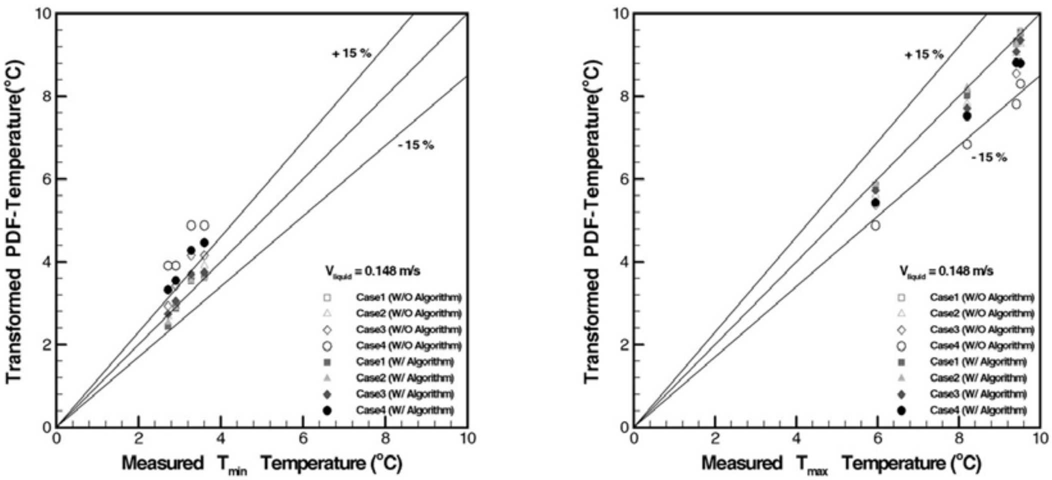


Fig. 9 Phase distinctions by the developed algorithm

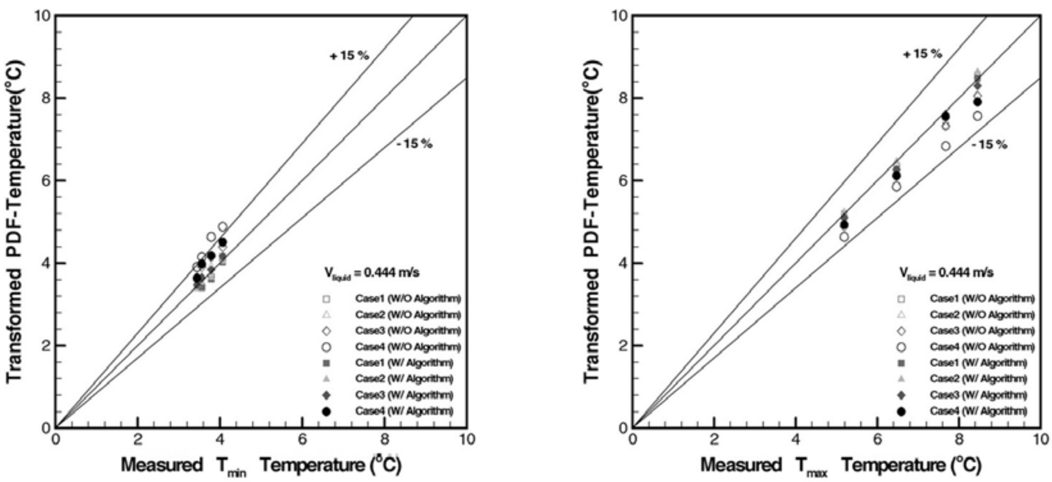
calculated results show that the algorithm can separate regions that temperature changes exist.

The comparisons of two transformed temperatures into PDF from the original raw data and the calculated data by the developed algorithm are shown in Fig. 10. The first transformed temperatures into PDF are determined from the obtained raw data, directly. The second transformed temperatures into PDF are obtained as transforming data, which are calculated by the developed algorithm. The open symbols mean the transformed temperatures into PDF from the original raw data and the closed symbols mean those from the calculated data by the developed algorithm. The subscripts, min and max mean in the cases when the optical copper intercepts the laser and when the heat source reaches the hot junction, respectively. That is, $T_{\min}$ means transformed liquid temperatures into PDF and $T_{\max}$ means transformed laser beam temperatures into PDF undergoing temperature change by the optical chopper. And the measured temperature means averaged liquid and laser beam temperature in the steady state, not undergoing temperature change by the optical chopper.

The results show that the PDF transformed temperature obtained from the calculated data by means of the developed algorithm is more accu-

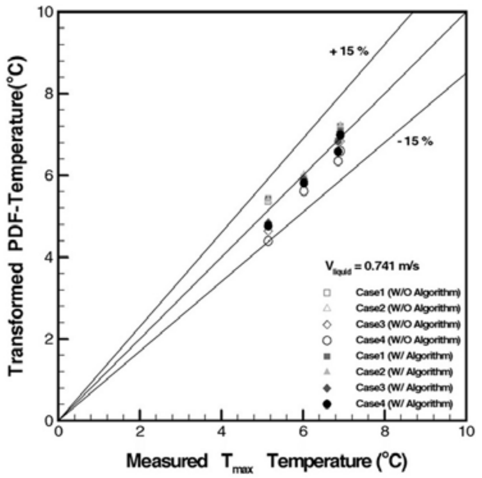


(a) V_{liquid}=0.148 m/s

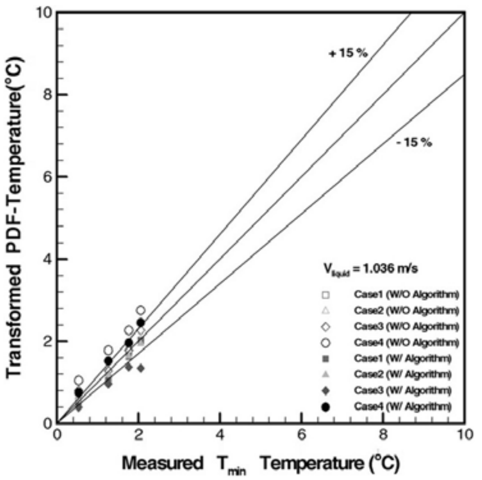


(b) V_{liquid}=0.444 m/s

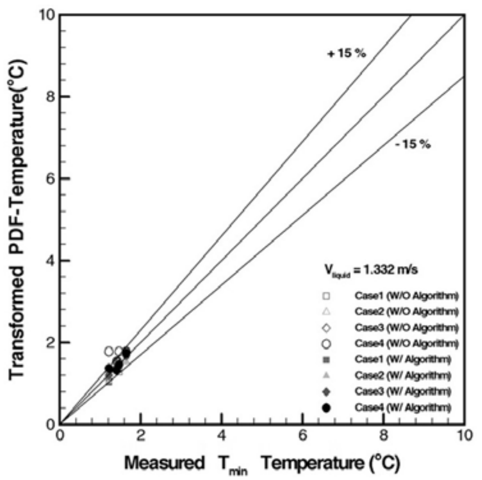
Fig. 10 Comparison of measured and transformed temperature into PDF



(c) $V_{liquid}=0.741$ m/s



(d) $V_{liquid}=1.036$ m/s



(e) $V_{liquid}=1.332$ m/s

Fig. 10 Comparison of measured and transformed temperature into PDF rate than the PDF transformed temperature obtained directly from the raw data. According to the experimental results, the developed algorithm can distinguish phases and estimate each temperature quite accurately. 95% of data is within $\pm 15\%$ error. Also, even if the temperature of the hot junction does not reach the steady state, the algorithm more accurately estimates the temperature.

Moreover, the directly transformed liquid temperature into PDF from the original raw data is estimated to be higher than the actual temperature. And the directly transformed laser beam temperature into PDF from the original raw data is estimated to be lower than the actual temperature. The reason is that the hot junction of the micro-thermocouple undergoes cyclic temperature differences, which is made by the optical chopper, in state that the residence time at the hot junction is shorter than its time constant. However, experimental results show that the developed algorithm compensates the measured temperature to an actual temperature to reduce errors.

5. Conclusions

In this study, a micro-thermocouple having a diameter of 12.7 μm has been fabricated and an algorithm to estimate each temperature of phases was developed, when phase changes exist at the hot junction of the micro-thermocouple. The response time of the micro-thermocouple was measured by dynamic calibration and it showed to have several milliseconds. The newly proposed algorithm was verified by conducting experiments simulating phase changes using an optical chopper and laser. According to the experimental results, the developed algorithm estimate 95% of temperature data within $\pm 15\%$ error.

It will be possible to measure more accurate liquid temperature in subcooled boiling with the fabricated micro-thermocouple and developed algorithm.

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