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THERMOCOUPLE HEATING IMPACT ON THE TEMPERATURE MEASUREMENT OF SMALL VOLUME OF WATER IN A COOLING SYSTEM

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Abstract

Experimental and numerical analyses have been performed to investigate the heating impact of using a thermocouple for the temperature measurement of a small volume of cold water (~ 24mm^3), due to thermal conduction through the wires. Two sizes of K-type thermocouple, 80µm and 315µm, were used to measure the temperature of cold water inside a small, thermally regulated chamber within a Centeo TG40 cooling system. The results show that thermal conduction from the ambient environment into the cold water produces a heating effect. This effect decreases for greater submersion depth of the thermocouple junction and is eliminated when the thermocouple junction is close to the copper bottom of the chamber. The inclusion of an insert into the chamber increases the thermal resistance between the copper block and the water, raising the heating effect of the thermocouple. The cooling effect of the copper block on the water is diminished when the air gap between copper block and plastic insert is increased, consequently raising the temperature inside the small well. Moreover, increasing the water height inside the large well has a negligible effect on the temperature of the small well.

Keywords: Temperature measurement, thermocouple heating impact, air-water system, numerical modelling

1. **Introduction**

Thermocouples can have an impact on the temperature of an object being measured due to heat conduction through the wires when the wires are exposed to a surrounding environment with temperature different to the measured temperature. This heat transfer occurs through the wires which then disturbs the system, causing an error in the temperature measurement [1-6]. This thermocouple heating effect can be reduced by decreasing the temperature difference between the thermocouple probe and external environment or reducing the size of thermocouple wires and their thermal conductivity [6, 7].

Many studies have observed that altering the thermocouple type (i.e. changing the wire materials) or geometry (i.e. changing wire diameter) has a strong impact on thermocouple measurement error. Wires with higher thermal conductivity exhibit larger measurement error because of parasitic thermal conduction along the wires between the object being measured and the surrounding environment. Attia et al. [1] studied the effects of different thermocouple material properties (E, J and T) and the surrounding material on temperature measurement inside the body. They showed that an increase in thermocouple thermal conductivity augmented heat transfer and thus underestimated temperature readings. Dow [5] pointed out that because of their high thermal conductivity, alumina tubes produce a greater error than resin-glass when used as an insulation material for thermocouple wires. Numerical results of Kidd [8] used the skin-technique to confirm that pairing chromel-constantan wires gave a lower conduction error than other materials used for thermocouple wires. Experimental results of Boelter and Lockhart [9] showed that iron-constantan gives a higher error in temperature measurement than Chromel-Alumel. Shaukatullah and Claassen [2] described experimental results for the temperature measurement of a chip surface with different thermocouple sizes and attachment methods. They reported that using a small diameter of thermocouple with lower thermal conductivity minimised thermocouple wire conduction error.

One solution to this error is to increase the length of the thermocouple wires in contact with the object being measured, decreasing the thermal gradient present along the wire closest to the junction. Tarnopolsky and Seginer [7] observed that a thermocouple with lower thermal conductivity (Type K) requires 60% less contact length than one with a higher conductivity (Type T). Fang and Ward [10] used two sizes of thermocouple to measure the temperature at the interface between liquid water and its vapour. Two Type K thermocouples, 25.4 µm and 80.3 µm were used. The wires of 24.5 µm were extended horizontally within the measured medium to a length that equalled 20 times their junction diameter to avoid any possible conduction error. However, the wires of the larger size thermocouple (80.3µm) were extended to 110 times their junction size.

The type of thermocouple electrical insulation also affects temperature measurement. Boelter and Lockhart [9] confirmed that there is a negligible effect from electrical insulation on temperature measurement when the thermocouple diameter (including the insulation) is less than the critical radius. Mohun [11] discussed the effect of electrical insulation for temperature measurement inside a solid wall, showing that the presence of electrical insulation over a critical length can only affect the thermocouple reading if the wires pass through a variable environmental temperature. Tszeng and Zhou [12] used the finite element method to analyse conduction error through thermocouple wires when the probe was in direct contact with the surface. They showed that when the heat flux along the thermocouple wire insulation surface is small and the thermocouple is fine, the effect of insulation on thermocouple probe temperature is negligible. They recommended using bare wire with a small diameter rather than a larger diameter thermocouple with insulation [12]. Woolley [13] confirmed that alumina oxide Al_2O_3 insulation causes higher measurement error than glass braid insulation during temperature measurement at the interface between aluminium and sand during a metal casting process. These results were demonstrated for different sizes of thermocouples and for very high temperature differences (~1500K), showing that a small thermocouple size gave minimal percentage error in temperature measurement [13]. Ahmed [14] recently studied the effect of an electrical insulation on temperature measurement and reported that different stripped lengths of insulation also had a negligible effect on temperature measurement.

Kulkarni et al.[4] verified that the flow around a thermocouple probe generates an increased heat transfer coefficient, and that this consequently causes an error in temperature measurement. They demonstrated that when a thermocouple probe is placed close to the wall, the measurement error is increased due to the rapid acceleration and convection flow developing over the boundary. However, this error is minimised when the flow Reynolds number is relatively low. Heitor and Moreira [15] showed that the existence of a thermocouple probe in the flow direction changed the flow behaviour, particularly during preparing flow for combustion. Moreover, the thermal interaction between the probe and surrounding fluids generates more perturbation. Rabin [16] proved that the behaviour of flow inside a measured system affects measurement error; in particular, laminar flow around the thermocouple produced a greater measurement error than that of the turbulent flow.

Hindmarsh et al.[17] showed that the presence of a thermocouple junction affects a water droplet freezing when it is suspended by a thermocouple to measure its freezing stages. Conduction through the wires forced the freezing to begin from the centre toward the outer surface of the water droplet. Xu and Gadala [18] demonstrated that high thermal conductivity fluid surrounding a thermocouple wire increases the error in measurement due to conduction through the wires. During surface cooling by water, the error is larger than that of the air cooling due to the difference in high heat transfer coefficient. However, Rabin [16] showed that an increase in the length of the immersed thermocouple wires inside the flowing fluid leads to a reduction in the error due to the conduction of heat through the wires. Moreover, Rabin confirmed that the effect of the conduction can be minimised when the size of the thermocouple is small. Specifically, Heitor and Moreira [15] showed that in order to minimise the conduction error the length-to-wire diameter of the wire should be 200.

In the present study, two different sizes of thermocouple (80μm and 315μm) were used to measure the temperature of a small volume of cold water inside a chamber in the micro-well of a thermostatically controlled system (TG40).

Centeo's TG40 is a mobile device, allowing temperature control of a SBS (Society for Biomolecular Screening) microplate, that permits researchers to monitor temperature during the experimental process. The TG40 protects samples against sudden temperature variation while they are being transported around a lab during an experiment. This can be done for a maximum of 30 minutes using a built-in battery [19]. In addition, the TG40 microplate can be connected to an external power supply through a docking station for recharging the built-in battery. Moreover, the TG40 device can be connected to an external computer to programme the temperature of each row.

The TG40 system consists of five rows of rectangular copper blocks of eight chambers per row. Plastic part(s) made of cyclic olefin copolymer (COC) can be inserted into each copper block. The maximum working range of temperature of the copper block was between 4^{o}C and 60^{o}C. However, in this study the temperature of the first row was adjusted to 4^{o}C, while the last one was set to 20^{o}C with a temperature difference of 4^{o}C maintained between every two consecutive rows. There are two wells per-chamber inside the plastic insert, a small well (with volume about 4mm^3) and a large well (with volume about 32mm^3), both are filled with water. Two lids cover all chambers, separating them from the outside environment.

The objective is to study the heating impact of a thermocouple(s) on the temperature measurement of a small volume of water in a cooling system. The small volume of water studied was inside a chamber in the first row of the TG40 cooling system. Ultimately, the preferred method to study the thermal behaviour of the system would be to exclusively use numerical modelling as this avoids any perturbations caused by measurement. However, this approach requires a validation against experimental measurements before numerical results can be solely used to examine the temperature distribution inside the large and small wells.

2. **Experimental techniques**

2.1 **TG40 model description**

The TG40 system consists of five rows of rectangular copper blocks of eight chambers per row (See Fig. 1). Each chamber has two wells which were filled with water in the experiments as shown in Fig. 2.

The first row was adjusted to 4^{o}C, while the last one was set to 20^{o}C with a temperature difference of 4^{o}C maintained between every two consecutive rows. The base of the chamber was made of copper, while the material of the plastic insert was cyclic olefin copolymer (COC) and the first and second lids were made from polystyrene. The properties of COC are 0.15 [W/ (m K)], 1020 [kg/m^3] and 1340-1466 [J/ (kg K)] for the thermal conductivity, density and heat capacity respectively. Whereas, the properties of the polystyrene are 0.14 [W/(m K)], 1065 [kg/m^3] and 1340-1466 [J/(kg K)] for the thermal conductivity, density and heat capacity respectively [20-24].

The thicknesses of the first lid, second lid, and the air gap between them were 80µm, 1100µm, and 550µm respectively.

2.2 **Experimental setup and measurement procedure**

Fig. 1 shows the experimental setup, which consisted of three main parts: the base holding the TG40 cooling system, micrometer movement, and PICOlog data acquisition TC08 system, which converted the thermocouple signal into data read by a computer.

The main objective of this study was to predict the temperature inside the small well. However, the thermal impact of the thermocouple on the small well will be very large due to the small volume of liquid it contains (about $4mm^3$), together with the experimental difficulty of reproducibly positioning the thermocouple probe inside the well. Therefore, experimental work concentrated on only measuring the temperature of the large well. Upon obtaining a satisfactory agreement between the experimental and simulation results, the prediction of the temperature inside the small well can be solely based on the numerical simulation. The two thermocouples used were type-K with bare wire diameters of 80µm (250µm including PFA insulation) and 315µm (600µm including PFA insulation)[1], (See

[1] The manufacturer of both thermocouples is Labfacility with codes Z2-K-2 X 5 and Z2-K-5.0-C81-MP for 80µm and 315µm respectively.

Table 1). These were employed to measure the temperature inside the large well in order to study their heat impact effect on the measurement.

The starting point of the thermocouple measurement was when the probe came into contact with the water surface, noticeable by the sudden drop in recorded temperature or by viewing the probe with a digital microscope. Thermocouple measurements were recorded at each 0.25mm step below the surface; this movement was controlled by a micrometre. Five experiments were performed for each thermocouple size, with an average sixty-second duration for recoding the temperature at each step. The measured average environment temperature was equal to 18^{o}C.

The actual water height was therefore measured by the distance travelled by thermocouple tip, as measured from the micrometer as it moved between the water surface and the bottom of the large well (See Fig. 1). The average water height was found to be approximately 6mm.

An identical set of experiments was repeated by filling the copper block with an amount of water to obtain the equivalent height of the water inside the plastic insert. The copper block (no plastic insert) experiments were performed to predict the copper block temperature which was used as a boundary condition for the numerical model (See section 6.2.3).

2.3 **Thermocouple calibration**

Thermocouple calibration was performed by comparing the thermocouple reading when fully submerged in crushed ice and boiling water with the standard water freezing and boiling temperature respectively [24]. A Pyrex beaker of two litres was filled with crushed ice, and the thermocouple probe was immersed for a sufficient length of time to avoid any outside temperature effects on the reading. Additionally, during the calibration process an appropriate distance was left between the thermocouple probe and the bottom of the beaker to prevent the effect of heat transfer with the beaker base. Freezing or water boiling standard temperature was considered (to 2 d.p.) to be those at standard atmospheric conditions (e.g. 1 atm) where water boils at 99.98°C[2] and freezes at 0°C [25] .

3. **Uncertainty analysis**

The uncertainty of the experimental results is presented in Fig. 3 and Fig. 4 which were calculated based on the fixed (bias) and random errors. According to Moffat [26], the uncertainty analysis should include the following:

1. The fixed error, $\boldsymbol{B_{X_i}}$
2. The precision index of the mean, $\boldsymbol{S_{\bar{X}_i}}$ which is calculated from

$$S_{\bar{X}_i} = \frac{S_{X_i}}{\sqrt{N}} \quad (1)$$

where N represents the number of samples and S_{X_i} is precision index of a single reading

$$S_{X_i} = \sqrt{\sum_{i=1}^{N} \frac{(X_i - \bar{X}_i)^2}{N-1}} \quad (2)$$

where X_i is a single reading and $\bar{X}_i$ is the mean of the experimental data.

3. The degree of freedom $\boldsymbol{\nu}$ which is related to the precision index which is equal to $\boldsymbol{N-1}$.

Therefore, the uncertainty analysis for 95% confidence level is calculated from

$$U_{0.95} = \left\{\left(B_{X_i}\right)^2 + \left(tS_{\bar{X}_i}\right)^2\right\}^{1/2} \quad (3)$$

where $\boldsymbol{t}$ is the student's factor of 95% confidence [27].

4. **Experimental results**

Fig. 3 shows the experimental results of the water temperature distribution inside the copper block measured by thermocouples of sizes 80µm and 315µm respectively.

The plastic insert-water system results demonstrate a similar trend to the results of copper-water system as shown in Fig. 4. Fig. 4 shows the experimental results of the water temperature inside the plastic insert measured by thermocouples of sizes 80µm and 315µm.

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[2]The boiling point of 99.98°C was used in accordance with the strict two-point calibration of Vienna Standard Mean Ocean Water (VSMOW) and as used elsewhere in the literature, see e.g. R. Tillner-Roth and D. G. Friend, J. Phys. Chem. Ref. Data, vol. 27, No. 1, 199.

It can be seen from Fig. 3 and Fig. 4 that the error bars are larger for measurements of employing a thermocouple of size 80μm. Obviously, the probe size of the 80μm thermocouple is smaller than that of the 315μm thermocouple. Therefore, the possible reasons for the different effort bars are: for each run, the possibility of getting the same starting point, when the thermocouple probe touches water surface, is lower for the 80μm thermocouple in comparison to 315μm. Furthermore, the thermocouple is supposed to measure the temperature distribution along the middle line through the plastic chamber or the copper block. Therefore, it was not possible to position the thermocouple in exactly the same middle position during each experiment. Consequently, the error for each experimental run will be different. Secondly, the effect of surface tension on the thermocouple probe will vary the shape of the water surface around the probe and therefore the heat transfer interaction with the thermocouple probe is different each time.

5. **Mathematical Modelling**

Thermal analysis was conducted on a single chamber located in the first row (See Fig. 1). Free convection heat transfer was considered for the air gap(s), as well as for the water inside the well(s) (Fig. 2) assuming the *Boussinesq approximation* (for both air and water inside the chamber). Therefore, continuity and Navier-Stokes equations of incompressible steady-state flow behaviour can be written as follows [28]:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{4}$$

Navier-Stokes equations:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{5}$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{6}$$

$$\rho (u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z}) = \mu (\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}) + g [\rho_o - \rho] \quad (7)$$

The last term of Eq. (7) represents the body force acting in the vertical *z*-direction.

The energy equation describes the heat flow through the liquid and solid by considering convection terms in the equation as follows:

$$\rho\, Cp\, (u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial x}) = k (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) \quad (8)$$

Air density was calculated from

$$\rho_{air} = \rho_o \left[1 - \frac{T - T_{inf}}{T_{inf}} \right] \quad (9)$$

Water properties were considered to be temperature dependent and calculated from tables available in Bejan [28].

Laminar flow was considered in the simulation because the value of the *Grashof* number (*Gr*), Eq.(10); characterising the flow feature in the system is less than 10^9 for both air and water [28]. The *Grashof* number is calculated to be 64096.2 (with height H=30mm) for air and is equal to 4087.44 for water (with height H=5mm) with a temperature difference of $\Delta T = T - T_{inf} = 16^{o}$C. (See Table 2 for air and water properties).

$$Gr = \frac{g\beta (T - T_{inf}) H^3}{\nu^2} \quad (10)$$

In a system of two immiscible fluids, when the system is heated from above the occurrence of *anticonvection* is possible (Welander[29]). The water inside the TG40 system was effectively heated from above due to the higher outside air temperature. Welander [29] showed that for anticonvection to occur in the air-water system the ratio of the properties, $\mu_a \beta_a C_{pw} / \mu_w \beta_w C_{pa}$, should be greater than 9 or smaller than 1/9. However, in the TG40 system studied here the ratio $\mu_a \beta_a C_{pw} / \mu_w \beta_w C_{pa}$, using the air and water properties at 20^{o}C (See Table 2), becomes 1.217, which is much lower than 9 and higher than 1/9.

The interface between air and water inside the chamber is considered to be stable with a continuous boundary. Therefore, a flat surface at the air-water interface was considered in the numerical simulation, essentially ignoring the effect of thermocapillary convection [29, 30].

6. **Numerical analysis**

The finite element method was used as implemented in COMSOL Multiphysics software. The thermocouple wires were treated as a very long fin and the temperature corresponding to the environmental temperature was determined [31]. Further details are shown in Al-Waaly [6]. Fig. 5 demonstrates that heating impact was greater for the thermocouple with larger size (315µm), as the heat interaction area with the outside environment is larger.

6.1 **Full geometry simulation**

In the numerical simulation, a half-geometry of the TG40 was considered due to its symmetry (as shown in Fig. 6a). The copper block was not considered in the simulation as its temperature was constant and the temperature gradient across the block's wall was assumed to be very small (See Fig. 2). Therefore, the air gap between the copper block and the plastic insert was considered to be an individual subdomain. The contact boundary between the air gap and the copper block was set to a constant temperature (4.05°C). Periodic boundary conditions were considered for the sides of the chamber that are connected to the other chambers in the same row. The upper surface of the second lid was subject to free convection at the atmosphere. The water height inside the large well has been discussed in section 6.2.1.

6.2 **Simulation without the model lids**

6.2.1 Water depth inside the large well

Several parameters affect the water depth inside the large well of the plastic insert (or copper block). These are, for example, manufacturing tolerances, an increase in water height due to thermocouple immersion, complex geometry of the water surfaces which are formed due to the surface tension between the water and plastic inserts (or the copper block) as well as between the thermocouple probe and water surface (See Fig. 7). Furthermore, due to the complex geometry of the water surface, a flat surface is assumed in the numerical simulation, as shown in Fig. 6a [29], (See section 6.4).

6.2.2 Simulation with the plastic insert

The lids were removed and a thermocouple inserted to measure the temperature inside the large well. Therefore, the upper surface of the plastic insert and each thermocouple wire were exposed to natural convection from the outside environment. A virtual air subdomain was therefore added and extended vertically to the point at which the thermocouple wires temperature was equal to the environmental temperature [32]. This additional subdomain implicitly calculates the heat transfer coefficients between the environment and thermocouple wires and the upper surface of the plastic insert (See Fig. 6b). A similar model can be used to analyse the water temperature using thermocouple size 315µm except the air domain height will be larger.

6.2.3 Simulation without the plastic insert

Experiment and numerical simulations were adopted for the copper block without the plastic insert to confirm the temperature of the block (See Fig. 6c). Water height inside the copper block was therefore assumed to be equal to the calculated value (6.25mm) when calculating its temperature (See section 6.4). This assumption can be seen to be acceptable by observing results for the plastic insert, where the water height inside the large well is very close to the measured value. The same boundary conditions were applied for the numerical analysis of the copper block-water model except the plastic insert was removed (See Fig. 6c).

6.3 **Simulation procedure and mesh resolution test**

A free meshing was used with tetrahedral elements. Small geometries were meshed using a fine mesh element size, particularly in and around the thermocouple wires and the probe (See Fig. 8). The convergence criterion (equal to 10^{-6}) for the numerical analysis was sufficiently small to achieve stable solutions, and it was tested that any further reduction in the tolerance did not change the numerically converged solutions.

Mesh dependence of solutions was also checked for the thermocouple probe temperature using two models for water height 6.25 mm at the thermocouple depth(s) of 0.5mm and 1mm below the water surface for 80µm and 315µm respectively (See Table 3). It can be observed in Table 3 that there is negligible change in the probe temperature when the total number of mesh elements were increased to more than

134240 and 82141 for 80μm 315μm respectively. Therefore, the last mesh size was selected for this case and for the consecutive cases.

6.4 **Numerical results and model validation**

Numerical simulation was performed with different values of copper block temperature for both sizes of the thermocouple: 80μm and 315μm, to predict the copper block temperature. Fig. 3 shows that the values of the copper block temperatures (4.05^{o}C and 4.1^{o}C) and (4^{o}C and 4.05^{o}C) give good agreement with the experimental data for the thermocouple sizes 80μm and 315μm respectively. Therefore, the value of the copper block temperature (4.05^{o}C) was adopted for the numerical analysis and during the experiments.

Three different heights were simulated (6mm, 6.25mm, and 6.5mm) for both sizes of thermocouple in the plastic insert-water model, as shown in Fig. 4. There is no fundamental effect of the water height on the simulation results. Therefore, the depth of 6.25mm gives good agreement between the experimental and simulation results for both thermocouples.

The starting point(s) (or the zero position of the thermocouple probe) of both simulations results in Fig. 3 and Fig. 4 was selected as the point at which the probe touched the water surface. Therefore, in the simulation the thermocouple probe measures the air temperature only, while this was not the actual case since the probe was still positioned at the interface between the air and water. Consequently, there is a jump in the simulation results of the first points in both Fig. 3 and Fig. 4.

Fig. 9 (a-b) shows the deviation of the experimental results from the numerical results. Fig. 9 was produced by comparing the average of the experimental results with numerical analysis. The main uncertainty in the measurement process was specifying the accurate zero position of the thermocouple probe in each run. Therefore, each of the experiments has its own starting position which differed between runs. This error affects the percentage deviation of the numerical results from the experimental results. Moreover, in the numerical simulation the assumption of a flat-water surface in both models can lead to more deviation from the experiments.

Fig. 9 also shows that the 315μm thermocouple deviates further from the numerical results than the 80 μm thermocouple. Due to its greater diameter, the possibility of an error identifying the starting zero position of the measurement is greater for the 315μm thermocouple. Moreover, the numerical analysis assumes that the probe has a spherical shape, which may lead to greater deviation from the numerical results as the actual shape of the probe is imperfect.

Fig.10(a-b) shows the heating impact both sizes of thermocouple have on the actual water temperature measurement in both the copper block and plastic insert models. Fig.10a shows that there is a greater effect at the first points in the copper block-water model, but that this decreases at deeper points below the water surface. Water temperature near the copper block (in the copper-water system) is approximately equal to the copper block temperature. During the experiments, part of the thermocouple wires was submerged within the water, while the remainder was exposed to free convection from the outside environment. When submerged deeper, the convection process can therefore eliminate the heating impact, regardless of the size of thermocouple as shown in Fig.10a. Therefore, the heating effect is approximately eliminated near the bottom of the copper block.

Fig.10b demonstrates similar behaviour to the results in Fig.10a except that the effect of plastic insert is apparent near the bottom of well where the thermocouple heating effect is still evident. The presence of the plastic insert increases the thermal resistance between thermocouple probe and copper block, leading to a larger impact of the thermocouple wire conduction. The effect of the thermal resistance, due to the presence of the plastic insert between the water inside the large well and the copper block, continues to deeper positions in the plastic insert experiments. The heating impact effect therefore continues to the final position, particularly for the larger thermocouple.

6.5 **Small well temperature distribution**

The TG40 was designed to maintain a uniform temperature inside the small well, holding it as close as possible to the copper block temperature. Two main parameters may affect the temperature of the small well: firstly, the water height inside the large well, and secondly, the air gap between the plastic insert and copper block. The existence of an air gap between the copper block and the plastic insert is inevitable due to the manufacturing tolerances of the TG40 device, see Fig. 2. An increase in the air gap below the small well will increase the thermal resistance between the water inside the well and the copper block. Consequently, the cooling effect of the copper block on the water inside the well will be reduced and the temperature inside the small well will rise, see Fig. 11a. A zero gap, which can be considered as a reference point, means the bottom surface of the small well is in direct contact with the copper. An increase in the air gap of 0-0.4 mm leads to a temperature difference of around 0.5^{o}C.

An increase in the water height inside the large well has a small effect in comparison to that of the air gap between the plastic insert and copper block. Fig. 11b demonstrates that an increase in water height inside the large well has a small effect on temperature distribution inside the small well.

7. **Conclusions**

The use of a thermocouple to measure the temperature of a small volume of liquid which is cooler than the environmental temperature can introduce a heating effect, that leads to measurement errors. This manifests itself as the readings obtained from the thermocouple being an overestimation of the real temperature of the liquid. Consequently, the reading from the thermocouple requires a correction to obtain a true value for the system being measured. The results obtained in this work showed that:

- A large sized thermocouple has a larger impact on the temperature measurement.
- The heating effect of the thermocouple decreases the deeper it is submerged into the liquid, and this effect is eliminated when the thermocouple junction is close to the copper block.
- An increase in the thermal resistance between the copper block and the thermocouple junction raises the heating effect of the thermocouple.
- The resistance to the cooling effect of the copper block is enhanced when the air gap between copper block and plastic insert is increased. Consequently, the temperature inside the small well is raised.
- An increase in the water height inside the large well has a negligible effect on the temperature of the small well.

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Fig. 1 Experimental setup for the TG40 cooling system with micrometre tool movement.

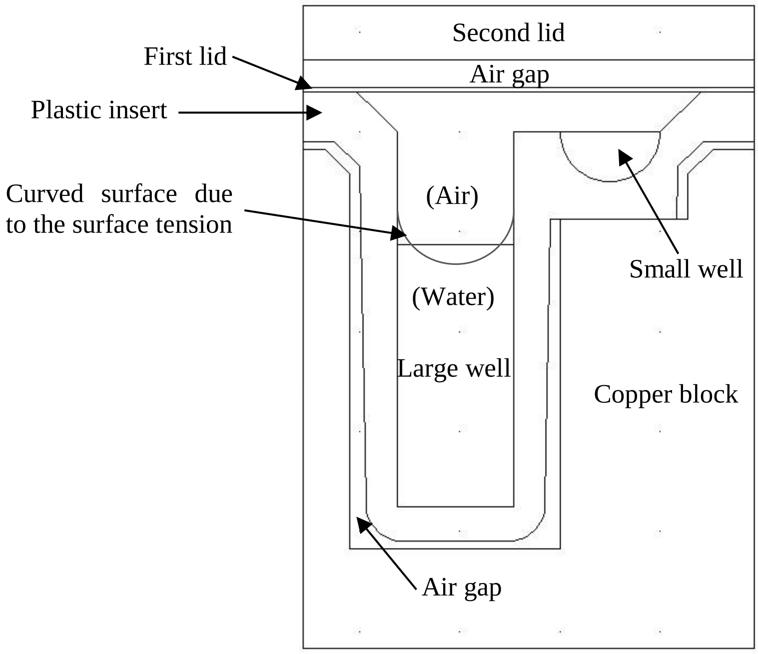

Fig. 2 Two-dimensional cross-sectional view of the chamber.

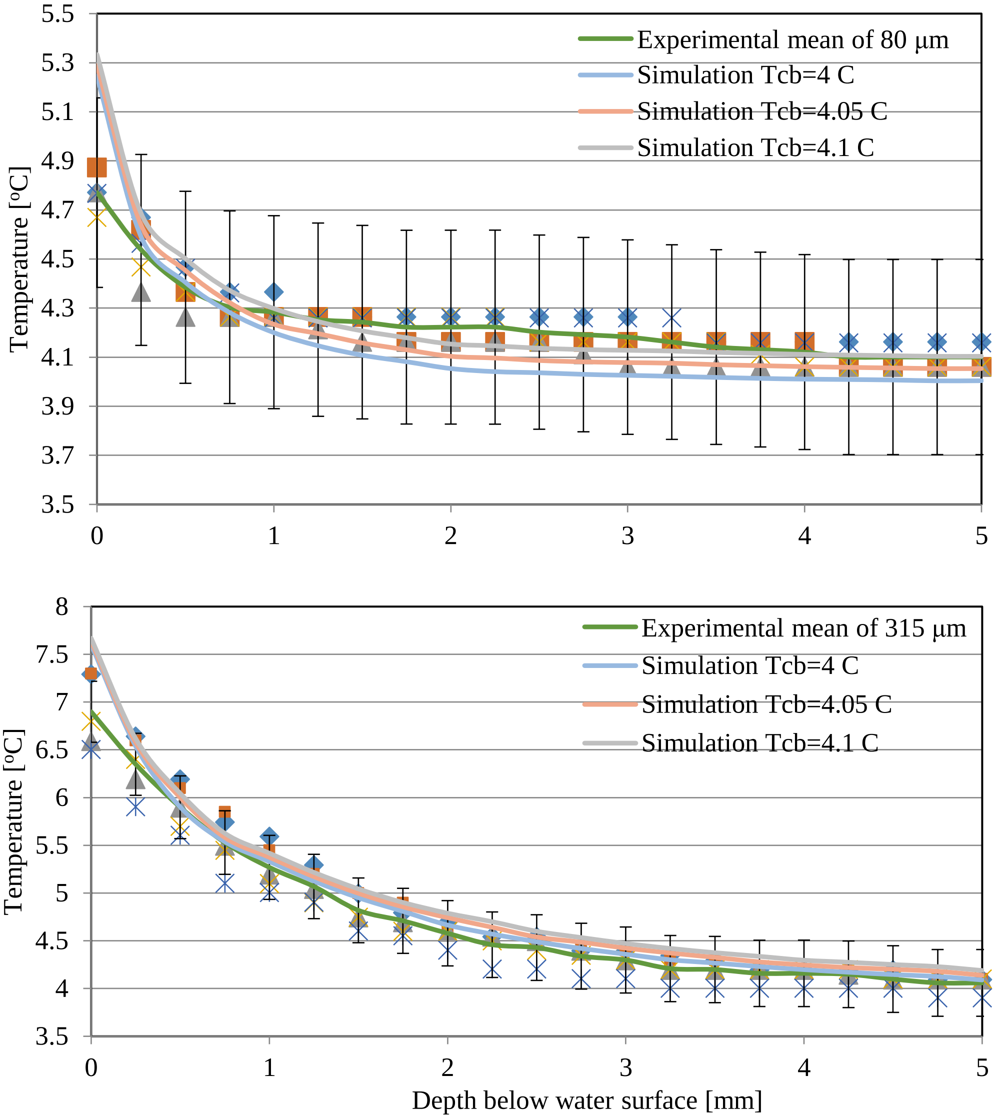

Fig. 3 Comparison between experimental and numerical results of water temperature distribution inside the copper block for both thermocouple sizes (80µm and 315µm) for different copper block temperatures. Error bars are ± uncertainty limit.

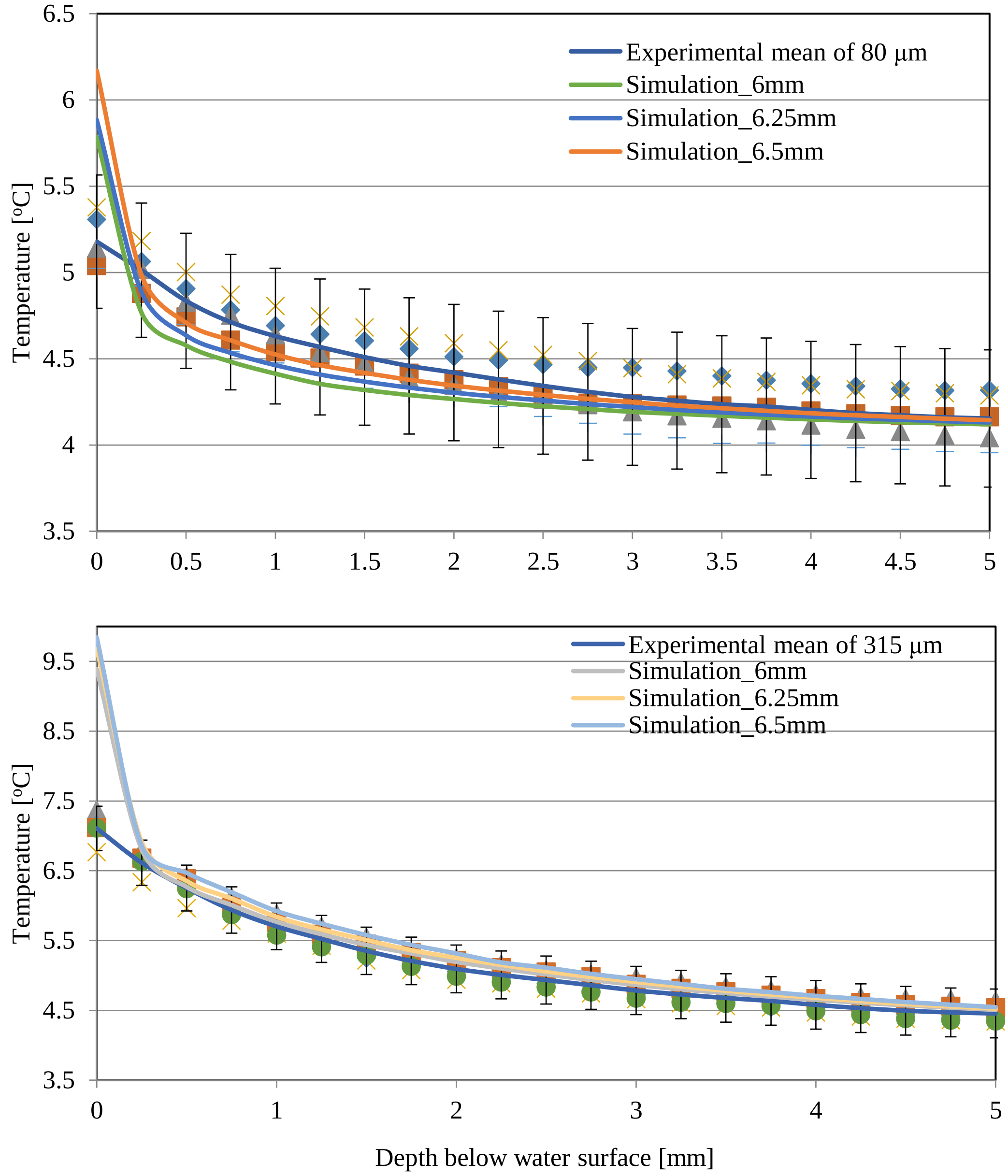

Fig. 4 Comparison between experimental and numerical results of water temperature distribution inside the copper block for both the thermocouple sizes (80µm and 315µm) for different copper block temperatures. Error bars are ± uncertainty limit.

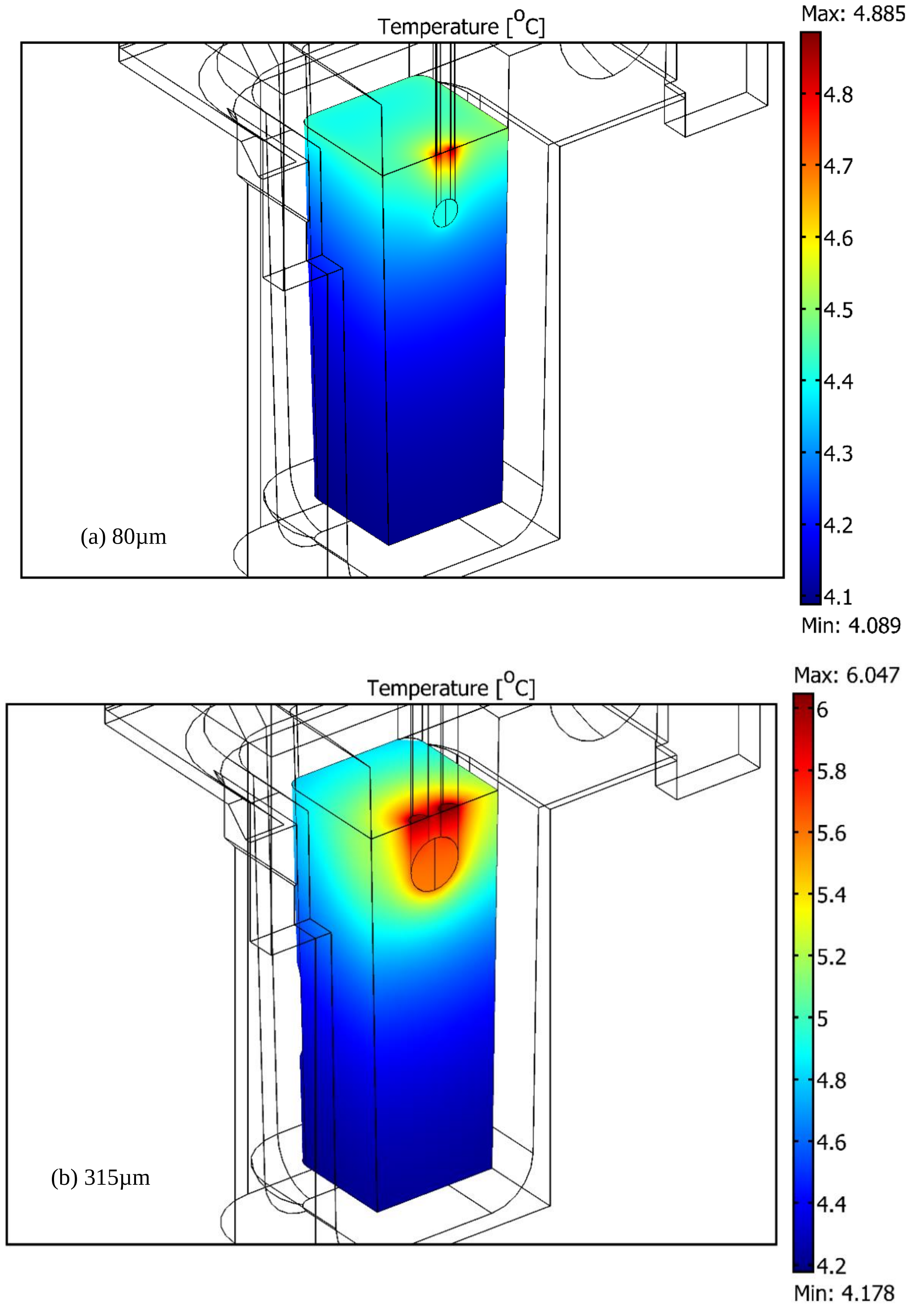

Fig. 5 Demonstration of the effect of a thermocouple on the water temperature inside the large well for 1.25mm depth: (a) 80 μm and (b)315 μm.

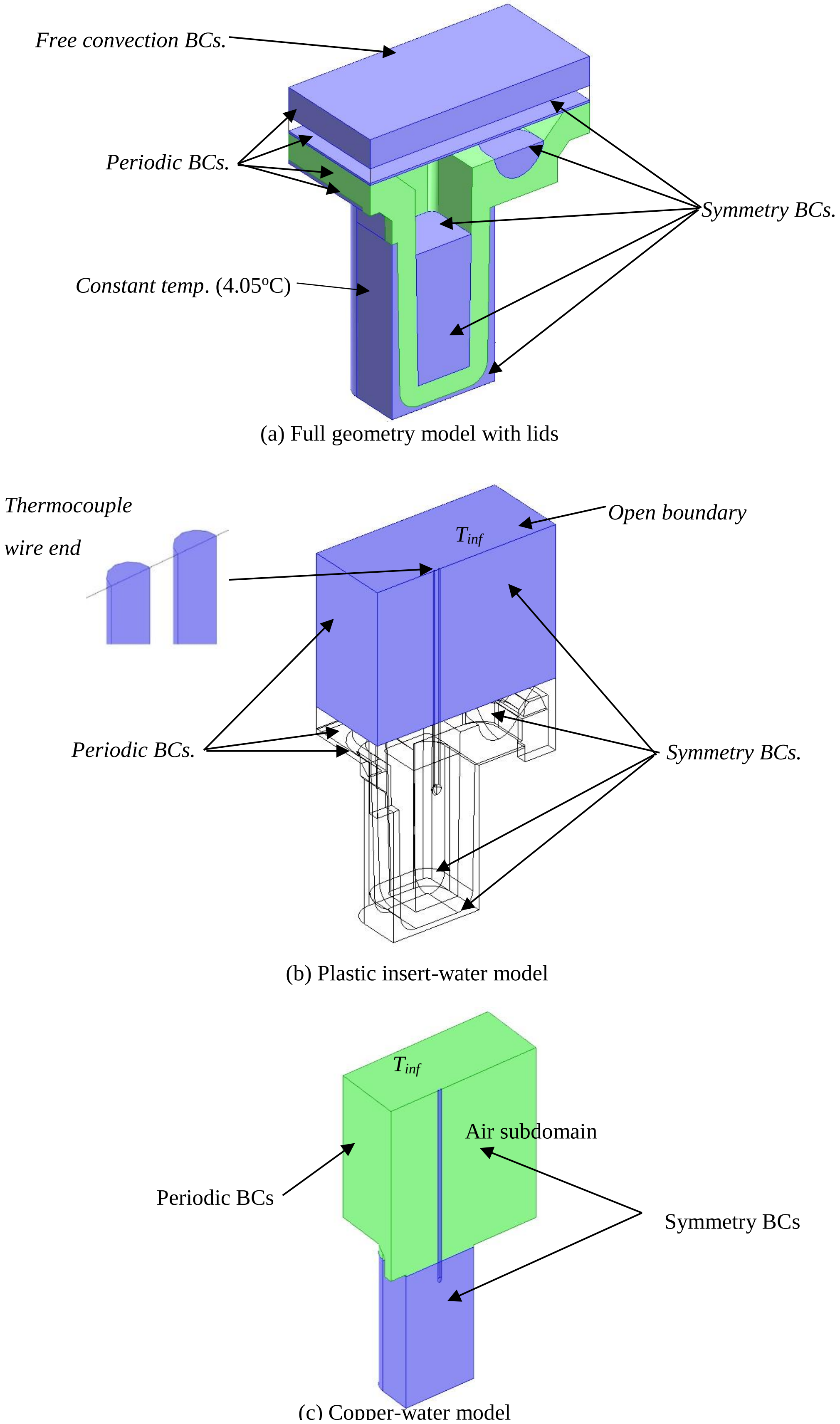

Fig. 6 3D geometry of a single chamber with boundary conditions: (a) Full geometry with lids, (b) without lids and with plastic insert and (c) copper block-water model.

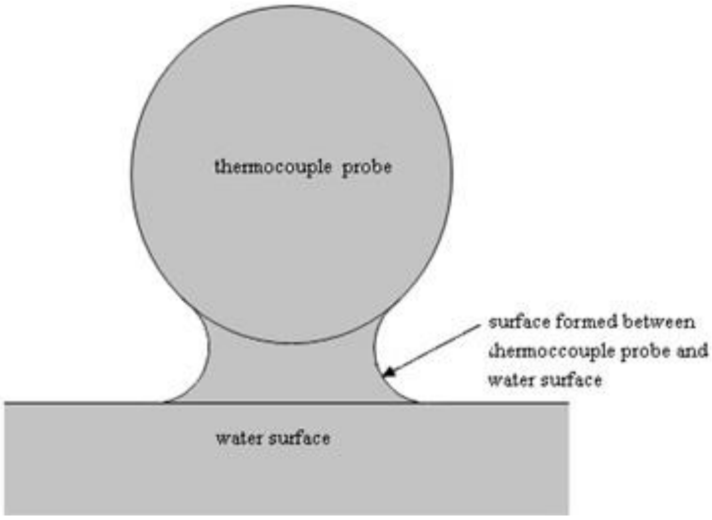

Fig. 7 Contact geometry between the water surface and thermocouple probe [33].

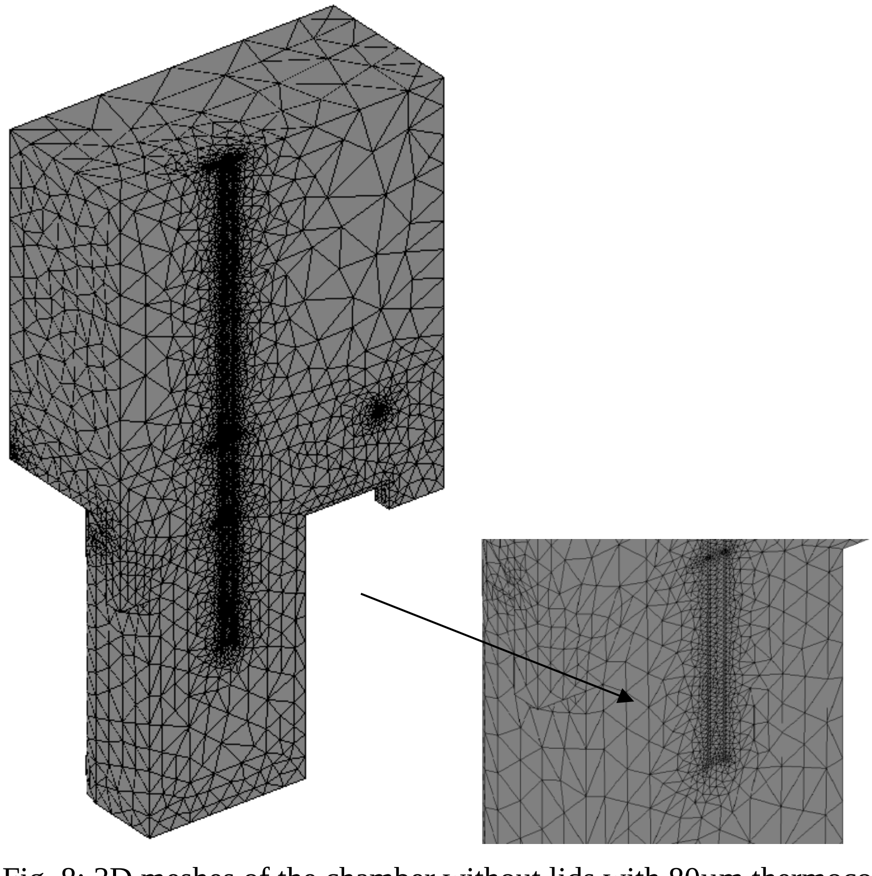

Fig. 8: 3D meshes of the chamber without lids with 80µm thermocouple.

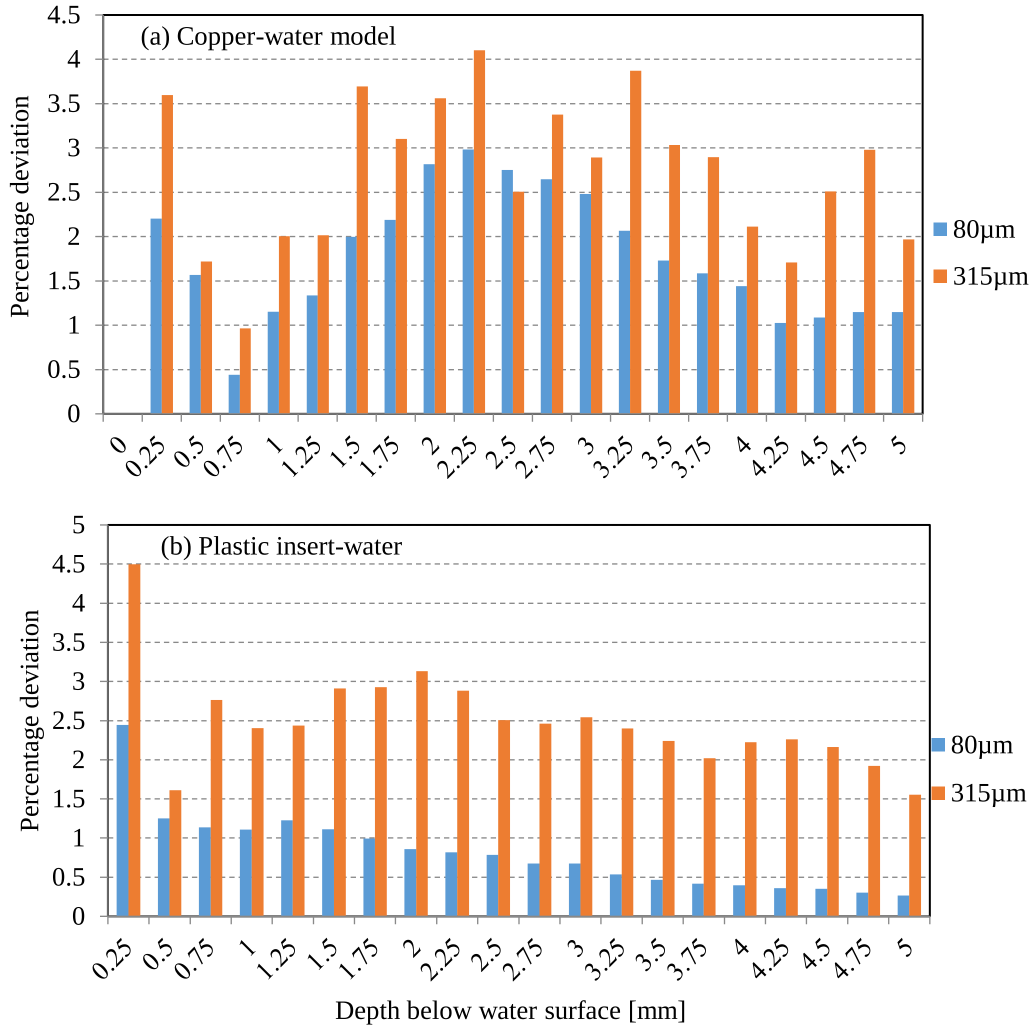

Fig. 9 Deviation of the numerical results from the experimental results for both sizes of thermocouple (80µm and 315µm): (a) copper block-water and (b) plastic insert-water models with copper block temperature equal to 4.05°C.

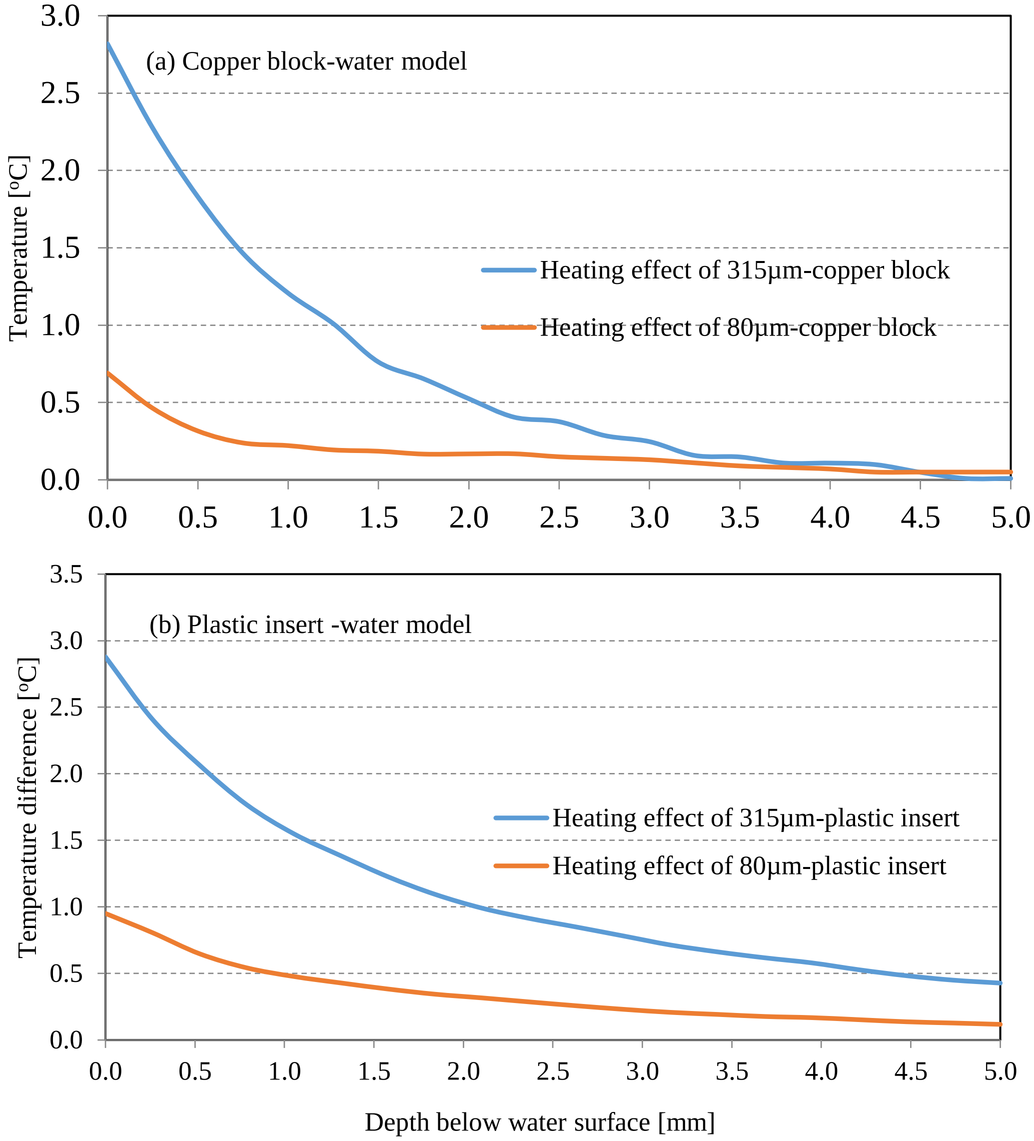

Fig.10 Comparison between the impact of both sizes of thermocouple: (a) copper block-water and (b) plastic insert-water models. The y-axis represents the difference between experimental mean results and simulation results without a thermocouple.

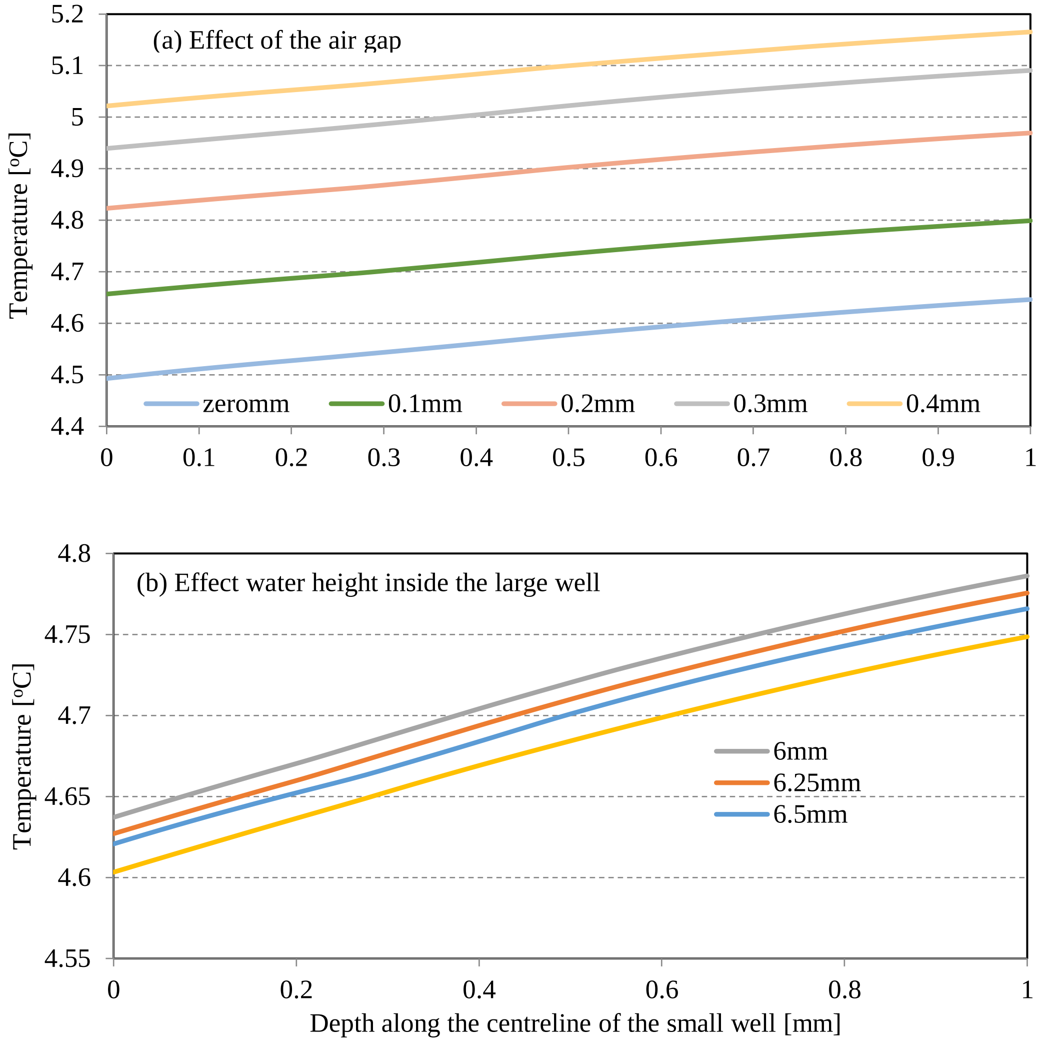

Fig. 11: Temperature distribution along the centre line inside the small well: (a) effect of varying the air gap and (b) effect of water height inside the large well. X-axis represents the distance along the centre line starting from zero mm (well bottom surface) to 1 mm (water surface in the well), see Fig. 2.

Table 1 Thermocouple type K material properties.

Thermocouple wire components	Thermocouple wires properties of Type K [24]		Thermocouple insulation properties, [PFA] [34]
	Chromel	Alumel	
Thermal conductivity [W/(m K)]	19.2	29.77	0.3
Density [kg/m^3]	8730	8600	7900
Heat capacity [J/(kg K)]	447.7	523.34	500

Table 2 Air and water properties at atmospheric pressure and 20°C [28].

Air		Water	
$v_a[m^2/s]$	15×10^{-6}	$v_w[m^2/s]$	1.004×10^{-6}
$\beta_a[1/K]$	3.403×10^{-3}	$\beta_w[1/K]$	2.1×10^{-4}
$\mu_a[kg/m.s]$	18.1×10^{-6}	$\mu_w[kg/m.s]$	10.02×10^{-4}
$C_{pa}[kJ/kg.K]$	1.006	$C_{pw}[kJ/kg.K]$	4.182

Table 3 Mesh dependent solution for thermocouple probe temperature with the plastic insert.

No. of mesh elements	Probe temperature, 315µm size (at depth 1mm)	No. of mesh elements	Probe temperature, 80µm size (at depth 0.5mm)
64697	5.526	90139	4.407
76863	5.769	112232	4.4135
82141	5.7695	134240	4.4155

List of symbols

Symbol	Definition
g	Gravitational acceleration [m/s^2].
C_p	specific heat capacity at constant pressure [J/kg K].
H	Height [m].
k	Thermal conductivity [W/m K].
p	Pressure [Pa].
T	Temperature [K].
T_{inf}	Environment temperature [K].
u	Velocity component in the x-direction.
v	Velocity component in the y-direction.
w	Velocity component in the z-direction.
β	Thermal expansion coefficient [$1/K$].
ρ	Density [kg/m^3].
ρ_o	Reference density [kg/m^3].
ν	Kinematic viscosity [m^2/s].
μ	Dynamic viscosity [m^2/s].
Subscripts	
a	Air.
w	Water.