Influence of water temperature on results of current meter calibration and measurement

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Abstract: On the basis of the results of calibration of current meters at water of varying temperatures, a hypothesis that water temperature influences measured water velocities was formulated. The analysis of our long-term data showed that the water temperature does have an influence on measured water velocity. This influence can be taken into account for practical purposes as a contribution to the uncertainty of measurements. The influence depends on the type of current meter propeller. This paper presents results obtained for the Ott C-2 current meter with propellers of the types 1, 2, 3, 5 and 6. Our analysis showed that the uncertainty is equal or less than 5% for measurements carried out in water with temperatures above 8°C. The differences between measured water velocities for water temperatures 5°C and 20°C reached maximum 6% (depending on the propeller) in a slowly flowing water (rotational frequency $n = 1 \text{ s}^{-1}$). For rotational velocity $n \geq 2 \text{ s}^{-1}$ the differences between velocities measured at water temperatures 5 and 20°C were mostly under 3%. The less influenced propeller is of type 3 for which the uncertainty of measurement does not reach 5% even for water temperature 1°C if the rotational frequency is bigger than 0.7 s^{-1} .

Keywords: Current meter; Measurement uncertainty; Water temperature influence.

INTRODUCTION

The Czech Calibration Station of Current Meters, the accredited calibration laboratory at the T. G. Masaryk Water Research Institute, has a somewhat unique position among laboratories of this kind, because our calibration tank – which can also be used as a big hydraulic flume – is fed with water from the Vltava River. Thus the water temperature varies in a quite wide range during the year – roughly from less than 1°C up to about 22°C. Because current meters are commonly used all year long the water temperature effects might be important from a practical point of view. Current meter manufacturers do not state a recommended temperature interval for their use.

During a review of the literature we found only a few works dealing with this problem. Staubli (1988) only mentions that there is some temperature effect but without any other comments. Thibodeaux (1994) in his very extensive literature review mentions Johnson's research which was carried out on several Neyrpic meters. Johnson found that a change of water temperature of about 17°C caused a maximum error of 6.2%. Zubík and Žoužela (2009) carried out measurements at a special stand with one Ott C-2 current meter with three propellers. The stand allowed changing temperature of water from 2 to 50°C. Their research shows that temperature does affect the results of measurements. However, in our opinion, using only one current meter and a quite limited amount of measurements do not allow a precise quantification. Niemiec and Starý (2010) carried out similar research with three current meters (two Ott C-2 with together 5 propellers and one Ott C-31) with water temperature varying from 2°C to 23°C. Their results are quite consistent, but again the total amount of current meters used was small.

THEORETICAL BACKGROUND

The influence of water temperature on water velocity measurement by propeller-type current meters can manifest itself in four distinct fields, namely: 1. temperature expansion of current

meter material, 2. temperature changes of viscosity of filled-in oil, 3. temperature changes of water density, and 4. temperature changes of water viscosity. Friction resistance in bearings is not taken into account because the ball bearings used in all contemporary current meters as a standard have a minimum resistance.

The influence of material temperature expansion is assumed to be negligible on the basis of the dimensions of a current meter and its parts. Moreover, clearances will apparently increase with decrease of temperature.

Viscosity of the oil filling will vary with temperature but there is no information available on the viscosity of the recommended oil from the Ott company. According to engineer-toolbox.com the change of viscosity for motor oils and diesels is almost of one order for a temperature change from 0 to 20°C. We can thus assume a similar change.

Water density varies with temperature only negligibly – about 0.2% when the temperature increases from 4 to 20°C but the change of the kinematic viscosity in the same temperature range is around 55%. When the water temperature changes from 0 to 20°C, the change of water viscosity reaches almost 80%. Unfortunately, there is no way how to separate these individual temperature influences.

Let us have also a look at the hydraulic resistance of current meter propellers and at the possibility of them being influenced by temperature.

Let us suppose a helical propeller of a helix pitch h (m). Then, for an ideal current meter in an ideal fluid, the flow velocity v (m s^{-1}) is

$$v = hn, \quad (1)$$

where n is the frequency of propeller rotation (s^{-1}). For a real current meter in a real fluid, there is the additional effect of friction of the fluid on the propeller blades surfaces and a resistance of their leading edges. These forces together with the other influences mentioned above cause the propeller rotation to be slower than the theoretical one. Because magnitude of the fluid friction as well as the resistance of the leading edge are

functions of Reynolds number (see e.g. Henderson, 1966) and thus, as Reynolds number is a function of viscosity, also of temperature. So it is evident that water temperature will influence results of calibration and measurements if carried out at other temperature than the temperature during calibration.

EXPERIMENTAL DATA

Our calibration database was exploited and data for several Ott C-2 current meters were chosen for analysis. The basic criteria were 1. the current meter was calibrated with at least 3 propellers at least 3 times with every propeller in water of various temperatures during the last years; 2. a good condition of the current meter can be supposed as well as proper and regular maintenance.

On the basis of these criteria eight current meters were selected giving a total of 35 combinations of meter body plus propeller. This selection provided a total of 317 calibration equations; for their distribution amongst particular types of propellers see Table 1. The temperature t of the water during calibration varied from about 1°C to 22°C.

Table 1. Number of calibrations for particular propellers.

Propeller No	No of calibrations
1	59
2	83*
3	61
5	60
6	54

* after removing data for an anomaly behaving propeller, 62 calibration equations were used.

WORKING HYPOTHESES AND METHODOLOGY

On the basis of our experience and previous work, several questions were put down as working hypotheses:

1. Does a temperature influence exist?
2. Is the temperature influence the same for all types of propellers?
3. Is the temperature influence the same for all meters with the same type of propeller?
4. If the temperature influence does exist, is it possible to quantify it?

Because our calibration software does not allow exporting primary calibration data, only hardcopy prints of calibration certificates, relevant calibration equations were used to compute velocities. The calibration equation is determined in accordance with ISO 3455 in the form

$$v = \alpha_i + \beta_i n, \quad (2)$$

where v is the flow velocity, α_i and β_i are the calibration coefficients valid in the specified interval of rotational frequency n , $i \leq 3$. This approach also simplified the evaluation of results of calibration because it was possible to arbitrarily choose the rotational frequency n .

All used calibration data were transferred into Excel spreadsheets where auxiliary computations and preliminary analyses were performed.

As a first step, a set of rotational frequencies was chosen for every type of propeller, i.e. the frequencies $n = 0.5 - 1 - 2 - 3 - 4 - 6 - 8 - 10 - 12 - 15 - 18 - 21$ (s^{-1}) for propellers of the types 1 and 5 (pitch 0.05 m) as well as for propellers of the

types 2 and 6 (pitch 0.10 m) and $n = 0.2 - 0.5 - 0.7 - 1 - 1.5 - 2 - 2.5 - 3 - 4 - 5 - 7 - 10$ (s^{-1}) for propellers of the type 3 (pitch 0.25 m) and appropriate flow velocities v were computed from all calibration equations for every propeller.

As a second step, all velocities for every particular type of propeller were plotted together as separate datasets for every individual propeller as a function of the water temperature t for the given rotational frequency n – for an example see Fig. 1.

These sets of graphs were used to appraise the temperature influence upon particular propellers and upon particular types of propeller.

The third step was finding an empirical model and evaluation of the dependence of velocity on temperature for quantifying the temperature influence. The data for individual propellers were aggregated for the individual propeller types and transferred into the SigmaPlot 2000 software by SPSS Inc. which was used for subsequent analyses. The main problem in this third step was finding an adequate empirical model. Preliminary analyses showed that for the given rotational frequency n a simple empirical model

$$v = y_0 + \frac{a}{t} \quad (3)$$

described the data quite well. In the model, v is the flow velocity ($m s^{-1}$), t is the temperature of the water during calibration ($^{\circ}C$) and y_0 ($m s^{-1}$) and a ($m s^{-1} ^{\circ}C$) are empirical coefficients. In this model, the value of the coefficient y_0 should be close to the product of the propeller pitch and the rotational frequency. Thus

$$y_0 = k + bn, \quad (4)$$

where k and b are empirical coefficients and n is the rotational frequency. At the same time the value of the coefficient b should be close to the propeller pitch. Concerning the coefficient a , we are not able to make any assumption because no clues exist.

RESULTS AND DISCUSSION

A rigorous analysis of graphs $v = f(t)$ (for an example see Fig. 1) showed that an influence on calibration results by water temperature does exist for all types of propellers, but in varying degrees. This conclusion was confirmed by the results of the regression analysis (see below). From a visual analysis of these graphs it is also apparent that all propellers of the same type are influenced in about the same degree. One exception from this result was found – one of the six propellers of the type 2 showed distinctly smaller velocities for higher rotational frequencies than all other propellers of this type. A visual check of this propeller did not show any marks of damage or any other clue so that we are not able to explain this anomaly which is evidently a property of this propeller because all other propellers calibrated with the same meter body behaved in a standard way. The data for this propeller were therefore removed from subsequent analyses.

By regression analysis we determined the empirical constants y_0 and a in the empirical model together with all basic statistics for all chosen rotational frequencies for all types of propellers – for an example see graph of function (3) at Fig. 2. The coefficients y_0 and a were then plotted as functions of rotational frequencies – see Fig. 3 and 4 – and regression analysis was applied to them.

Fig. 1. Velocity as a function of temperature for rotational frequency $n = 8 \text{ s}^{-1}$ for all propellers of type 1 (numbers of current meter bodies in legend).

Fig. 2. Example of result of regression analysis for propeller 3 and rotational frequency $n = 3 \text{ s}^{-1}$.

Fig. 3. Empirical coefficient $y_0 = f(n)$ ($v = y_0 + \frac{a}{t}$).

The proposed model for the coefficient y_0 (Eq. (4)) is evidently valid, the coefficient k of this model is small and the coefficient b is close to the propeller pitch as it was supposed. Because we did not have any theoretical solution for the second coefficient, a , a simple linear model

$$a = c + dn \quad (5)$$

Fig. 4. Empirical coefficient $a = f(n)$ ($v = y_0 + \frac{a}{t}$).

was used. Results of these analyses are summarized in Table 2. The results are statistically significant with $p < 0.0001$ for all types of propellers. Table 2 presents the main result of our study. It can be used to calculate the uncertainties in measured water velocities for various differences between water temperatures during current meter calibration and measurement.

We are aware of some drawbacks of the overall model (see Eq. (3)), namely that it is entirely empirical, and that the value of the velocity grows above all limits as temperatures approach zero degrees, which is physically impossible. On the other hand, in the temperature range of about 1–22°C the model approximates the data very well, moreover it is quite simple and the results are statistically significant in almost all cases with $p < 0.01$ and in all cases with $p < 0.05$ in spite of the fact that outliers were not removed. This is not valid for the more sophisticated models we tried. The unremoved outliers probably caused the normality test to fail in several cases, but in our opinion the results are still usable.

As can be seen from Fig. 4, the temperature influence varies according to the type of the propeller. The propellers subject to the strongest influence are those with a minimal pitch – propellers Nos. 1 and 5 with the pitch $h = 0.05 \text{ m}$. The least influenced propeller is the propeller of type 3 with the pitch $h = 0.25 \text{ m}$. It is interesting that while the slope of the regression lines for coefficient a is practically the same for the propellers 1 and 5 with the same pitch $h = 0.05 \text{ m}$, for propellers 2 and 6 with the same pitch $h = 0.1 \text{ m}$ the slope distinctly differs. This difference is probably caused by the geometry of the propellers.

Knowing that both of the coefficients in our empirical model (Eq. (3)) can be described by linear models, let us use them in Eq. (3) which can now be rewritten as

$$\begin{aligned} v &= y_0 + \frac{a}{t} = k + bn + \frac{c + dn}{t} = \\ &= \left(k + \frac{c}{t} \right) + \left(b + \frac{d}{t} \right) n = \alpha' + \beta' n. \end{aligned} \quad (6)$$

The result of this substitution and formal rearrangement has the shape of the standard calibration equation; for this reason the symbols α' and β' were used. Both of these coefficients are temperature dependent and they are plotted as functions of temperature in Figs 5 and 6.

Table 2. Values of coefficients of the empirical temperature model for all propellers (models $v = y_0 + \frac{a}{t}$, $y_0 = k + bn$ and $a = c + dn$; R^2 is a coefficient of determination).

Propeller No	y_0			a		
	k	b	R^2	c	d	R^2
1	0.0289	0.0549	0.9998	0.0346	0.0018	0.9044
2	0.0147	0.1037	1.0000	0.0164	0.0006	0.8815
3	0.0043	0.2544	1.0000	0.0089	0.0008	0.9261
5	0.0425	0.0550	0.9999	0.0251	0.0019	0.9946
6	0.0285	0.1030	1.0000	0.0171	0.0014	0.9858

It is apparent from Fig. 6 that the influence of temperature on the coefficient β' is almost negligible and that, similarly to the results plotted in Fig. 3, the values of this coefficient for propellers with the same pitch are almost the same and are very close to the pitch. On the contrary, the coefficient α' (see Fig. 5) is strongly temperature dependent and its values also vary with the type of the propeller.

Fig. 5. Coefficient $\alpha' = f(t)$ ($\alpha' = k + \frac{c}{t}$ – see Table 2).

Fig. 6. Coefficient $\beta' = f(t)$ ($\beta' = b + \frac{d}{t}$ – see Table 2).

From a practical point of view, more interesting than the absolute values of these coefficients are their relative values – possible uncertainties. The values of the coefficients at 20 °C were chosen as reference values and the values of relative differences

$$\Delta\alpha' = (\alpha'_t - \alpha'_{20}) / \alpha'_{20}, \quad \Delta\beta' = (\beta'_t - \beta'_{20}) / \beta'_{20} \quad (7)$$

Fig. 7. Change of the ratio $\Delta\alpha'$ with temperature ($\Delta\alpha' = (\alpha'_t - \alpha'_{20}) / \alpha'_{20}$, reference temperature 20°C).

Fig. 8. Change of the ratio $\Delta\beta'$ with temperature ($\Delta\beta' = (\beta'_t - \beta'_{20}) / \beta'_{20}$, reference temperature 20°C).

were computed and plotted. The symbols α'_t, β'_t are values of the coefficients at the arbitrary temperature t and $\alpha'_{20}, \beta'_{20}$ are the values of these coefficients at 20°C. It is surprising how an overall picture has significantly changed as can be seen from Figs 7 and 8. It is apparent that the magnitude of the relative differences $\Delta\alpha'$ (see Fig. 7) are quite considerable for low water temperatures and they depend, with an exception of the propeller of the type 3, on the diameter of the propeller and not on the propeller's pitch which, as a result, we are not able to fully understand. At this moment, the only possible explanation is that the shape of the propeller plays a basic role – the propellers 1 and 2 have the same diameter of 50 mm and two blades while the propellers 5 and 6 have a diameter of 30 mm and three

blades. The last propeller, of the type 3, has a diameter of 50 mm and three blades.

The relative differences $\Delta\beta'$ (see Fig. 8) are small and even for the water temperature of 1°C do not reach a value of 3.5% for propellers with the pitch $h = 0.05$ m and for propellers with a bigger pitch they are even less, for temperatures over 5°C they are even less than 0.5% for all pitches and so they are almost negligible.

When taking into account the absolute values of the coefficient α' and the ratio of the coefficients α' and β' it is apparent that the water temperature influence is bigger on propellers of a lesser pitch, as well as for lower temperatures and slower rotational frequencies.

In practice, the usable values of possible uncertainties can be computed quite simply as the ratio of velocity at a given temperature v_t and the velocity at a reference temperature v_{ref} according to Eq. (3) and (7) using the values of the coefficients given in Table 2 for any temperature in an interval 1–20°C and any rotational frequency. An example of such a calculation is given in Table 3 where the reference temperature was taken as 20°C.

In Table 4, some critical values for all propellers are given, namely the maximum value of the ratio v_t/v_{ref} (i.e. at water temperature 1°C and minimum rotational frequency), the temperature for which the ratio is less than 5% for the minimum rotational frequency, the minimum rotational frequency for which the ratio is less than 5% for temperatures 1°C and 5°C and the same parameters for the ratio less than 1%.

It must be underlined that these findings cannot be used for exact temperature corrections but only for estimating possible uncertainties. An extrapolation of the results cannot be recommended for temperatures exceeding approximately 22–25°C.

CONCLUSIONS

The analyses of the calibration equations proved that the results of calibration as well as the results of current meter measurements are influenced by the temperature of water.

The temperature effect is apparent for all types of propellers under consideration but varies according to the type of propeller and at the same time it is the same for all propellers of a given type.

The temperature effect is more substantial for lesser temperatures and lesser water velocities but for temperatures over 5°C and velocities over 0.15 m s⁻¹ the uncertainty does not reach 5% (see Tables 3 and 4).

Because current meters are calibrated in water of a given temperature but then are used for measurement in water with a widely varying temperature, this temperature effect should be taken into account in the case of measurement. In our opinion our results still do not allow a precise correction of the temperature effect so that this effect should rather be taken into account through an enlargement of the uncertainty of calibration constants according to ISO 748 (Table E.5 of this document). The method of estimating the uncertainties caused by water temperature is described above.

Table 3. Ratio v_t/v_{20} for propeller 1 at varying rotational frequencies n . Reference temperature 20°C (t is a water temperature, α'_t and β'_t are the temperature dependent coefficients in Eq. (6); $\alpha'_t = k + \frac{c}{t}$, $\beta'_t = b + \frac{d}{t}$ – see Table 2, $v_t = \alpha'_t + \beta'_t n$).

t (°C)	α'_t (m s ⁻¹)	β'_t (m)	n (s ⁻¹)											
	$k + c/t$	$b + d/t$	0.5	1	2	3	4	6	8	10	12	15	18	21
1	0.0635	0.0567	1.580	1.404	1.258	1.194	1.158	1.120	1.099	1.086	1.077	1.068	1.062	1.058
2	0.0462	0.0558	1.275	1.191	1.122	1.092	1.075	1.057	1.047	1.041	1.037	1.032	1.030	1.027
3	0.0404	0.0555	1.173	1.120	1.077	1.058	1.047	1.036	1.030	1.026	1.023	1.020	1.019	1.017
4	0.0376	0.0554	1.122	1.085	1.054	1.041	1.033	1.025	1.021	1.018	1.016	1.014	1.013	1.012
5	0.0358	0.0553	1.092	1.064	1.041	1.031	1.025	1.019	1.016	1.014	1.012	1.011	1.010	1.009
6	0.0347	0.0552	1.071	1.050	1.032	1.024	1.019	1.015	1.012	1.011	1.009	1.008	1.008	1.007
8	0.0332	0.0551	1.046	1.032	1.020	1.015	1.013	1.009	1.008	1.007	1.006	1.005	1.005	1.005
10	0.0324	0.0551	1.031	1.021	1.014	1.010	1.008	1.006	1.005	1.005	1.004	1.004	1.003	1.003
12	0.0318	0.0551	1.020	1.014	1.009	1.007	1.006	1.004	1.003	1.003	1.003	1.002	1.002	1.002
14	0.0314	0.0550	1.013	1.009	1.006	1.004	1.004	1.003	1.002	1.002	1.002	1.002	1.001	1.001
16	0.0311	0.0550	1.008	1.005	1.003	1.003	1.002	1.002	1.001	1.001	1.001	1.001	1.001	1.001
18	0.0308	0.0550	1.003	1.002	1.002	1.001	1.001	1.001	1.001	1.001	1.000	1.000	1.000	1.000
20	0.0306	0.0550	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 4. Basic critical values of water temperature and rotational frequency of the propeller for a given ratio v_t/v_{20} (i.e. uncertainty of the measurement) for all propellers (reference temperature 20°C).

Propeller	Max. v_t/v_{20}	$v_t/v_{20} < 1.05$			$v_t/v_{20} < 1.01$		
		t (°C) $n = 0.5$ (s ⁻¹)	n (s ⁻¹) $t = 1^\circ\text{C}$	n (s ⁻¹) $t = 5^\circ\text{C}$	t (°C) $n = 0.5$ (s ⁻¹)	n (s ⁻¹) $t = 1^\circ\text{C}$	n (s ⁻¹) $t = 5^\circ\text{C}$
1	1.58	8	> 21	2	16	>> 21	21
2	1.235	4	4	0.5	12	12	3
3	1.155	3	0.7	0.2	10	7	0.7
5	1.347	6	> 21	1	14	>> 21	15
6	1.209	4	4	0.5	12	>> 21	3

Acknowledgment. The work carried out in data analyses and preparation of this article was done in the framework of VÚV task No 9515 – Calibration of Current Meters.

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Received 9 August 2012
Accepted 4 February 2013