Thermodynamic-Temperature Data from 30 K to 200 K

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New measurements of thermodynamic temperature T with Dielectric-Constant Gas Thermometry (DCGT) were performed at PTB from 50 K to 200 K [1], see Table 1. Particular care was taken to check for possible systematic sources of errors by performing experiments applying three working gases, namely helium, neon, and argon, the polarizability of which differs by a factor of up to eight. Together with former DCGT values [2] of thermodynamic temperature the new results yield a consistent dataset in the range from 30 K to 200 K. This dataset is in good agreement with the newest results of Acoustic Gas Thermometry (AGT) [3] and Refractive-Index Gas Thermometry (RIGT) [4], which have quite different sources of uncertainty compared with DCGT. The combination of these DCGT, AGT, and RIGT data with the "*Estimates of the differences between thermodynamic temperature and the ITS-90*" [5], being as an appendix of the "*Mise en pratique for the definition of the kelvin in the SI*" the present-day recommendation of the *Consultative Committee for Thermometry*, yields a new function $T - T_{90}$ versus ITS-90 temperature T_{90} for the range from 35 K to 195 K, the uncertainty of which is reduced by a factor up to about four.

Table 1 Consistent new dataset $T_{DCGT} - T_{90}$ in dependence on T_{90} in the temperature range from 50 K to 200 K obtained with the latest generation of DCGT equipment [1]. $u(T_{DCGT} - T_{90})$ is the standard uncertainty of the weighted-mean value $T_{DCGT} - T_{90}$ that has been estimated in steps considering correlations. The data of this work have been obtained using capacitor C1 and/or C2.

T_{90} / K	$(T_{DCGT} - T_{90})$ / mK	$u(T_{DCGT} - T_{90})$ / mK	Gas	Capacitor
50	-1.86	0.30	^{4}He	C1
51	-1.93	0.27	^{4}He, Ne	C1+C2
60	-2.11	0.31	^{4}He, Ne	C1+C2
70	-3.09	0.39	^{4}He, Ne	C1+C2
79	-3.82	0.42	^{4}He, Ne	C1+C2
84	-3.74	0.43	^{4}He, Ne	C1+C2
100	-5.16	0.48	^{4}He, Ne	C1+C2
120	-5.06	0.65	^{4}He, Ne	C1+C2
200	-4.40	0.99	^{4}He, Ne, Ar	C1+C2

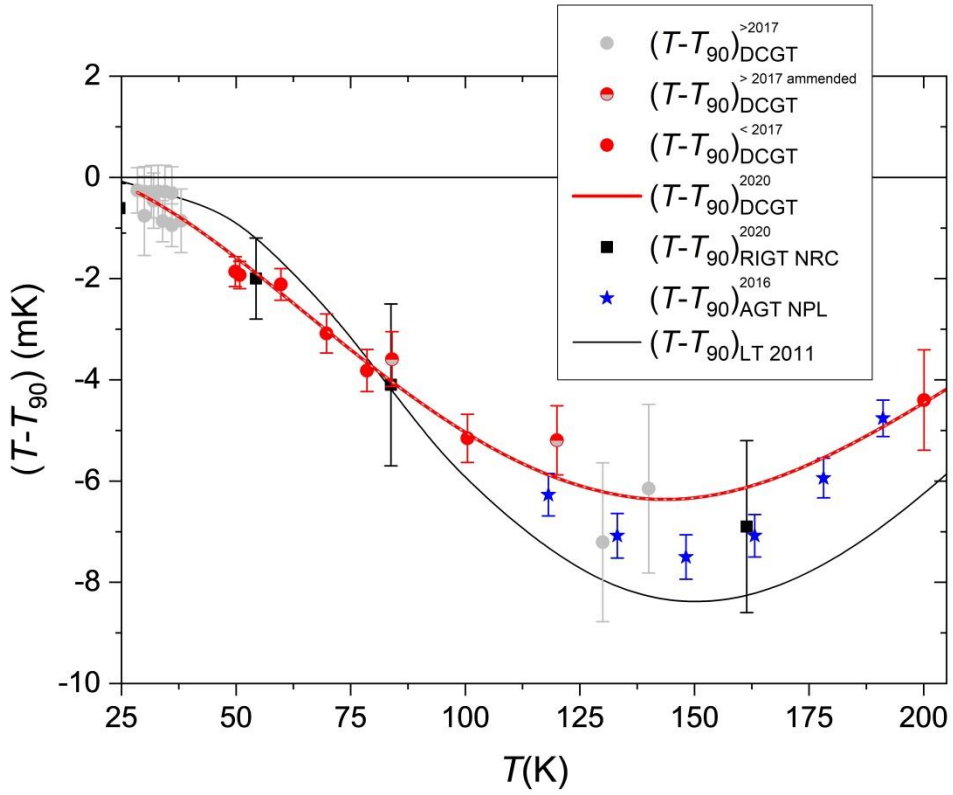

Figure 1 Recent determinations of the difference $T - T_{90}$ between thermodynamic temperature, T, and temperature on the ITS-90, T_{90}, obtained by different primary-thermometry methods. The bars represent the confidence interval corresponding to the standard uncertainty. The weighted mean DCGT values $T_{DCGT} - T_{90}$ are marked as follows: Filled red dots: New data listed in Table 1 [1]; Filled grey dots: Data published in [2]; Half grey and half red dots: Values from [2], readjusted at 84 K due to a new polarizability value of neon, and at 120 K due to an additional neon isotherm, respectively. The red line represents a fourth-order polynomial obtained from an unweighted fit to the DCGT data from about 30 K to 200 K (Polynomial (1), see below). The black line displays the best fit of a critical review of previous T - T_{90} determinations performed by a working group of the *Consultative Committee for Thermometry* [5]. (This function is called in [1] $(T - T_{90})_{LT2011}$). In addition, literature data are included for comparison: Blue stars: AGT by Underwood *et al.* 2016 [3]; Black filled squares: RIGT by Rourke 2020 [4].

Table 2: Overview of results for the differences between thermodynamic temperature, *T*, and temperature, T_{90}, on the International Temperature Scale of 1990 (ITS-90) at "base temperatures" selected in [5]. The second to seventh column contain recent data obtained by AGT [3], DCGT [1], and RIGT [4], respectively, and the accompanying standard uncertainty estimates $u(T\text{-}T_{90})$. The AGT and DCGT data have been deduced applying fourth-order polynomials fitted to the experimental pairs (T_{90}; ($T\text{-}T_{90}$)), see [1]. Columns eight to eleven show weighted-mean values together with their uncertainty estimates. Combination (1) considers the information given in the second to seventh column. Combination (2) includes also the values from [5]. The ($T\text{-}T_{90}$) values for combination (2) have been approximated by function $(T - T_{90})_{\mathrm{ARD2020}}$ (Polynomial (2), see below). All differences and uncertainty estimates are given in mK.

T_{90} / K	AGT[3]		DCGT[1-2]		RIGT[4]		Combination (1)		Combination (2)	
	($T\text{-}T_{90}$)	$u(T\text{-}T_{90})$	($T\text{-}T_{90}$)	$u(T\text{-}T_{90})$	($T\text{-}T_{90}$)	$u(T\text{-}T_{90})$	($T\text{-}T_{90}$)	$u(T\text{-}T_{90})$	($T\text{-}T_{90}$)	$u(T\text{-}T_{90})$
35			-0.64	0.29			-0.64	0.29	**-0.61**	0.28
45			-1.26	0.47			-1.26	0.47	**-1.20**	0.44
54			-1.92	0.29	-2.0	0.8	-1.93	0.27	**-1.90**	0.27
70			-3.06	0.39			-3.06	0.39	**-3.04**	0.38
78			-3.61	0.42			-3.61	0.42	**-3.59**	0.39
84			-4.04	0.44	-4.1	1.6	-4.04	0.42	**-4.05**	0.40
90			-4.44	0.46			-4.44	0.46	**-4.51**	0.42
100			-5.03	0.49			-5.03	0.49	**-5.17**	0.45
130	-6.95	0.44	-6.19	1.57			-6.89	0.42	**-6.98**	0.41
161	-7.16	0.42	-6.16	1.43	-6.9	1.7	-7.07	0.39	**-7.14**	0.39
195	-4.39	0.35	-4.76	1.05			-4.43	0.34	**-4.51**	0.33

Polynomial 1:

$$(T - T_{90})_{\mathrm{PTB2020}}/\mathrm{mK} = \sum_{i=0}^{4} a_i (T_{90}/\mathrm{K})^i \qquad (1)$$

with a_0 = 0.3260, a_1 = 0.013628, a_2 = -0.001506, a_3 = $1.0079 \cdot 10^{-05}$, a_4 = $-1.7443 \cdot 10^{-08}$.

Polynomial 2:

$$(T - T_{90})_{\mathrm{ARD2020}}/\mathrm{mK} = \sum_{i=0}^{4} b_i (T_{90}/\mathrm{K})^i \qquad (2)$$

with b_0 = 0.861199, b_1 = -0.023377, b_2 = -0.000588, b_3 = $1.293 \cdot 10^{-06}$, b_4 = $8.277\ 10^{-09}$.

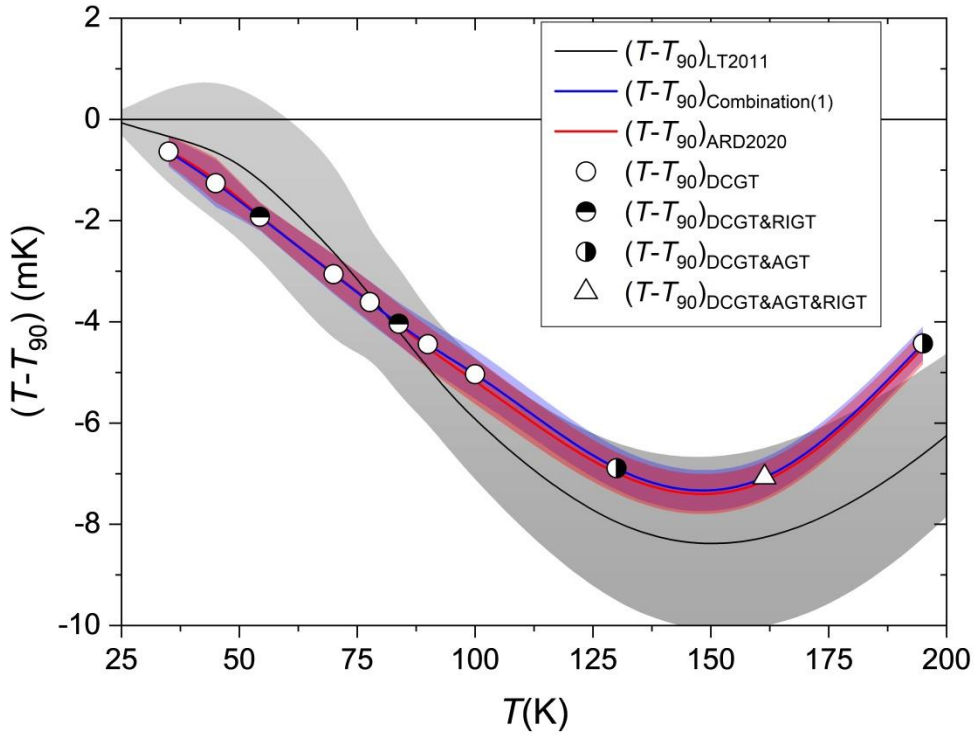

Figure 2 Estimates for the difference $T - T_{90}$ between thermodynamic temperature, T, and temperature on the ITS-90, T_{90}. The two functions $(T - T_{90})_{LT2011}$ (from [5]) and $(T - T_{90})_{ARD2020}$ (Polynomial (2)) are shown as black and red line, respectively. The corresponding shaded areas display the confidence intervals corresponding to the standard uncertainty obtained by spline interpolation. The symbols represent weighted-mean values of recent results obtained with AGT, DCGT, and RIGT, cf. Table 2. They are differently marked depending on whether it is a pure DCGT input or a weighted mean between DCGT & RIGT, DCGT & AGT or DCGT & AGT & RIGT. The blue line is a spline interpolation between all symbols (combination (1)).

[1] Gaiser C., Fellmuth B., Haft N., *Metrologia* **57**, 055003 (2020).

[2] Gaiser C., Fellmuth B., Haft N., *Metrologia* **54**, 141 (2017).

[3] Underwood R. *et al*., *Phil. Trans. R. Soc. A* **374**, 20150048 (2016).

[4] Rourke P.M.C. ,*Metrologia* **57**, 024001 (2020).

[5] Fischer J. *et al*., *Int. J. Thermophys.* **32**, 12 (2011).