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Thermophysical properties reference data for some key engineering alloys

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Abstract. A summary is given of the results of various NPL measurements carried out over a number of years on specimens of 310 and 430 stainless steel, Inconel 600, and Nimonic 75 alloys. The properties measured were thermal conductivity, λ, thermal diffusivity, a, specific heat capacity, C_p, and electric resistivity, ρ. Linear thermal expansivity values are also included to allow corrections to be made to the results of thermal measurements, including density, due to dimensional changes that occur on heating. Definitive NPL values are presented for selected thermophysical properties for three key engineering alloys, over the temperature ranges from ambient to 750 °C and for one alloy up to 500 °C.

In addition comparisons are made between the measured thermal conductivity values and those obtained indirectly from measurements of (i) thermal diffusivity, specific heat capacity, and density; and (ii) electric resistivity via the Wiedemann – Franz relationship. This comparison study is important, as thermal conductivity is often calculated when direct measurements are either not available or not possible. Overall, the average of the measured values of thermal conductivity and those calculated via measurement of electric resistivity agree to within 4%; and those calculated via measurements of thermal diffusivity, specific heat capacity, and density are in good to moderate agreement within 10%. For austenitic and ferrite steels and nickel – chromium alloys, calculation of thermal conductivity via electric resistivity has proved to be reliable and convenient and its use can be recommended. The derivation of thermal conductivity from thermal diffusivity is reliable, except at temperatures where phase changes occur.

1 Introduction

Thermal conductivity reference materials are an important requirement for thermal measurements since they can be used to validate and calibrate measurement apparatus. But while there has been significant development of insulating reference materials, driven mainly by energy-saving or environmental issues, there has been a noticeable lack of development of metals and alloys for the engineering sector (Tye 1996, 1999).

The recent emergence of new and often rather complex materials has stimulated development of new or improved measurement techniques, including that of thermal diffusivity by the laser-flash and other transient methods; and the need for reference materials has been further stimulated by development of various forms of contact transient multiproperty measurement techniques (Kubicár and Bohác 1999). High precision (say ±3%) claims are made for thermal properties with new techniques but some values, particularly of thermal conductivity, vary by amounts well beyond the claimed precision. In addition, there can be discrepancies between directly measured thermal conductivities and values derived via measurements of thermal diffusivity and specific heat capacity (Kubicár 2002).

Measurement inconsistencies create serious problems for the scientist or engineer who needs reliable properties information for a material and its application. There can be valid reasons for such differences, eg material anisotropy, but any proposed reference should have widely accepted values, not only for thermal conductivity but also for thermal diffusivity and specific heat capacity. Thermal expansion would also be of value, allowing correction for the effect of dimensional change on measured values of thermal conductivity, thermal diffusivity, and density. In general, such effects are less than 1% and are often neglected.

Under its standards programmes funded by the Department of Trade and Industry, NPL has been in the forefront of developing new reference materials, either participating in or leading measurement investigations conducted by national measurement laboratories (Tye and Salmon 2002). For example, the present conference contains a two-part paper describing the certification of thermal conductivity and thermal diffusivity values for Pyroceram 9606, a high-temperature ceramic.

The present paper describes and summarises work that has been in progress at NPL for a number of years on metals and alloys. Careful and repeated measurements of thermal conductivity (including electric resistivity) and thermal diffusivity have been undertaken up to 750 °C and above, by absolute longitudinal-bar and flash-diffusivity methods on several specimens of each material. In addition, specific heat capacity and thermal expansion measurements have been included that involved differential scanning calorimetry (DSC) and push-rod dilatometry, respectively.

2 Description of materials and test methods

Stocks of each material were acquired in the form of solid cylindrical bars having nominal diameters of 25, 50, and 75 mm, except for 430 stainless steel that was available only as 25 mm diameter bar. Details of the composition, heat treatment, and other relevant information are given in table 1.

Density measurements were made by weighing specimens cut from both ends of the rod, and weighing in air, m_a, and distilled water, m_w. The true density was obtained by use of the equation

$$\begin{aligned}\text{True density} &= d_m(d_w - d_a) + d_a, \qquad \text{where} \quad d_m = m_e/m_a \\ &= d_m \times 0.9976 + 0.0012 \,,\end{aligned}$$

Table 1. Typical composition, heat treatment, and density of alloys.

Element	Material			
	310 stainless steel	Inconel 600	Nimonic 75	430 stainless steel
	Composition			
C	0.06	0.065	0.103	0.05
Cr	25.05	16.05	19.7	17.1
Ni	20.3	balance	balance	0.36
Mo	0.2	–	–	0.14
Si	0.39	0.29	0.46	0.71
Mn	1.38	0.2	0.45	0.65
S	0.006	0.002	0.003	0.02
P	0.25	–	0.006	0.019
Fe	balance	8.25	4.15	balance
Co	–	0.02	–	–
Cu	–	0.05	0.01	–
Al	–	–	0.17	–
	Heat treatment			
	1050 °C for 1 h in dry pure H_2, dew point less than −50 °C, then water-quenched	1120 °C for 2 h in dry pure H_2, dew point less than −50 °C, then water-cooled under H_2	1080 °C for 1 h in dry pure H_2, dew point less than −50 °C, then water-cooled under H_2	750 °C for 1 h in air, then cooled naturally
	Density/g cm^{-3}			
	7.881	8.395	8.355	7.667

where d_m is the measured density, d_w is the density of water (0.998 g cm^{-3} at 17 °C), and d_a is the density of air (0.0012 g cm^{-3} at 20 °C).

3 Measurement methods

3.1 *Thermal conductivity*

Two different apparatuses were used for measurements on cylindrical rod specimens, both of which have been described fully elsewhere (Corsan 1992). The first was the NPL standard long-bar apparatus, designed to be the measurement standard for high-thermal-conductivity (>10 W m^{-1} K^{-1}) materials (figure 1). This is an absolute steady-state method operating in vacuum with a guarded heater at one end of the specimen and a water-flow calorimeter at the other. The specimen is enclosed within a multi-heater cylindrical guard shield designed and operated to ensure that lateral heat losses are minimised so as to be less than 3% of the total heat flux evaluated by numerical integration. The operating range is from 50 °C to 750 °C. The specimens are 25 mm in diameter, 320 mm in length, with cavities at each end for heater or calorimeter attachment. Temperature measurements are made at eight equidistant positions along the specimen with calibrated 0.25 mm diameter Nicrosil/Nisil (type N) thermocouples fixed in 0.55 mm diameter holes, 3 mm deep. For this and all subsequent machined specimens the tolerance is ±0.02%. Based on measurements of NBS tungsten, electrolytic iron

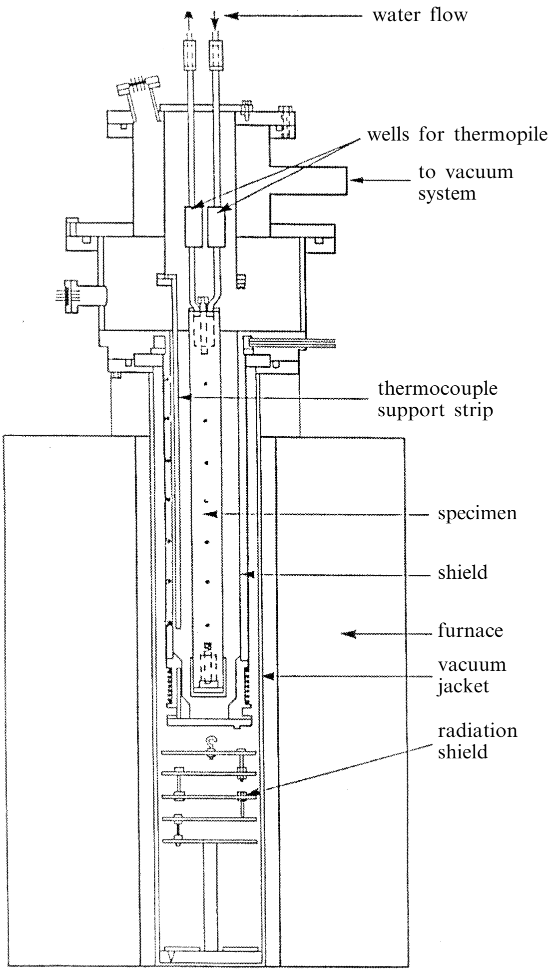

Figure 1. The NPL standard long-bar apparatus.

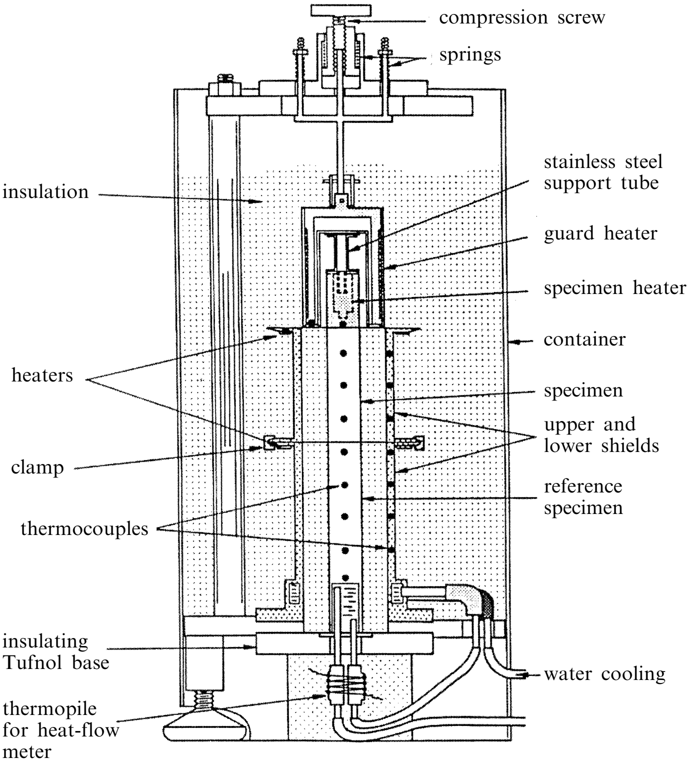

Figure 2. The NPL short-sample apparatus.

1464, and stainless steel 1462 standard reference specimens, the maximum uncertainty obtained was ±3%, and in general is less than ±2% over the full temperature range.

The second was the NPL short-sample apparatus (SSA), based on a simpler design for operation between 50 °C and 500 °C (figure 2). Whilst it is an absolute method, it also employs a reference material at the lower end of the heated specimen. A cylindrical guard system ensures that heat flow between the specimen and guard amounts to less than 2% of the total heat flux. The specimen size is 20 mm diameter × 70 mm long, and temperature measurements are made at three and five positions along the length of the specimen and reference respectively, with calibrated 0.25 mm diameter Nicrosil/Nisil (type N) thermocouples fixed in 0.55 mm diameter holes, 3 mm deep. The overall precision of the apparatus has been validated by comparison measurements with the NPL standard long bar, and by the apparatus used at the Physikalisch-Technische Bundesanstalt (PTB) in Germany (Corsan et al 1991). In the former measurements on the three NBS standard reference materials a maximum deviation of 3.1% was shown from the certified values, and in the latter the maximum difference between the two apparatuses was 3% at temperatures below 100 °C and considerably less at temperatures up to 500 °C. An overall estimate of the total uncertainty for this apparatus is ±4%.

3.2 *Thermal diffusivity*

Measurements were made with the NPL standard laser-flash system based on the original concept of Parker and colleagues (Parker et al 1961) and employing various corrections for radial heat loss, finite pulse duration, and non-uniformity of heat source (Maglić and Taylor 1992). The specimen size for this series of metals was 12 mm diameter and typically 1.5 mm thick. In all cases, a thin coating of graphite was applied to each surface to improve absorption on the heated face and increase thermal radiation from the rear face.

From the results of various intercomparison measurements at the NPL and other international laboratories on materials including high purity alumina, Pyroceram 9606, silicon, copper, and stainless steel SRM, the maximum uncertainty over the temperature range 50 °C to 1600 °C is estimated to be ±4%.

3.3 *Specific heat capacity*
This property was measured with a Netzsch DSC 404 twin-crucible differential scanning calorimeter at a heating rate of 20 °C min^{-1} over the approximate temperature range 50 °C to 900 °C in an argon atmosphere. The test specimen was a disc 5.5 mm in diameter and 1 mm thick. Three scans are made under 'closely identical' conditions with one crucible empty and the other, respectively, empty (to provide the baseline), containing a similar-sized sapphire reference disc (reference scan), and finally containing the test specimen. The specific heat capacity is then obtained from a comparison of the measurement and reference scans and corrected for any departure of the baseline from true zero. The overall uncertainty in the results is estimated to be within ±4%, based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%.

3.4 *Thermal expansion*
Expansivity was measured with a Netzsch 402 ED twin push-rod dilatometer on a specimen 6 mm in diameter and 25 mm long, with a heating rate of 10 °C min^{-1}. The measurement system is precalibrated with an NBS alumina reference specimen. The overall uncertainty in the results is estimated to be within ±4%, based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%.

3.5 *Electrical resistivity*
In all cases measurements were made by the conventional four-probe contact method on specimens machined for the short-sample apparatus (Corsan 1992). The experimental uncertainty is less than 0.5%.

Except for thermal expansion, measurements were undertaken on specimens cut from each end of a sample bar to investigate the consistency of the bar stock. Batch-to-batch consistency was examined by making measurements over a period of a few months. So far, work has been completed on specimens from the 25 mm and 50 mm stocks, and is continuing on specimens from the 75 mm stock.

4 Results

Typical experimental results on heating and cooling for thermal conductivity, electric resistivity, thermal diffusivity, and specific heat are shown for examples of one of the

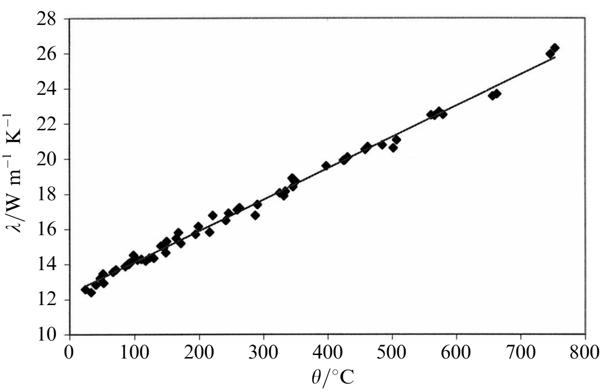

Figure 3. Thermal conductivity of 310 stainless steel specimens cut from the 25 mm diameter stock.

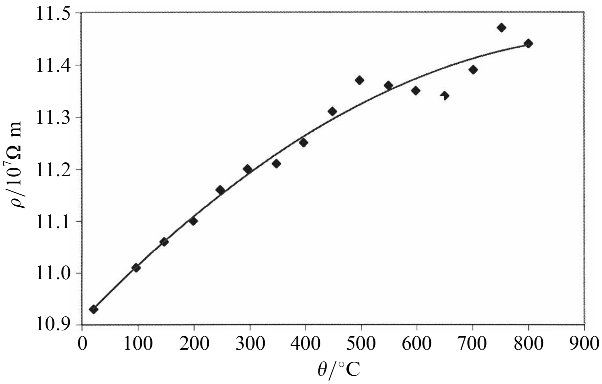

Figure 4. Electrical resistivity of Inconel 600 cut from the 25 mm diameter stock.

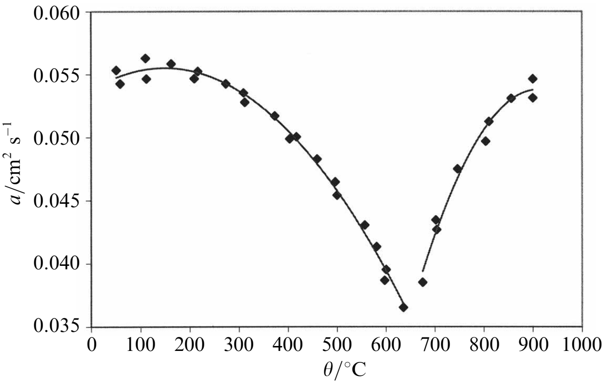

Figure 5. Thermal diffusivity of 430 stainless steel cut from the 25 mm diameter stock.

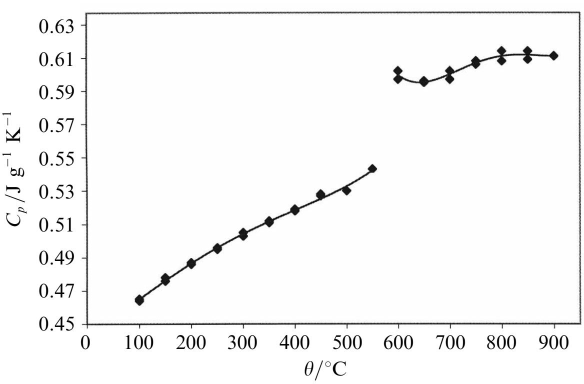

Figure 6. Specific heat capacity of Nimonic 75 cut from the 25 mm diameter stock.

individual materials in figures 3 to 6, respectively. For each specimen and material, a curve was fitted to the data points and values were tabulated.

5 Discussion

5.1 *Comparison of apparatus*

Experimental results for specimens cut from end A of the 25 mm diameter bar of each of the four materials measured in the two thermal conductivity apparatuses over the common temperature range are listed in table 2.

The results are very consistent for each material in each apparatus and agree to within a maximum of $\pm 2\%$ over their common temperature range. This is well within the estimated uncertainty for each apparatus and provides confidence in use of the

Table 2. Thermal conductivity of four materials measured in the NPL long-bar (LB) and short-sample (SSA) apparatuses. Percentage difference (%diff) between the results obtained is shown in parentheses.

θ/°C	Thermal conductivity/W m^{-1} K^{-1}											
	310 stainless steel			430 stainless steel			Inconel 600			Nimonic 75		
	LB	SSA	%diff	LB	SSA	%diff	LB	SSA	%diff	LB	SSA	%diff
50	13.2	13.0	(−1.9)	21.0	20.8	(−1.4)	13.4	13.5	(0.9)	12.8	12.9	(0.8)
100	14.1	13.9	(−1.4)	21.7	21.6	(−0.7)	14.2	14.4	(1.2)	13.6	13.8	(1.0)
150	15.0	14.9	(−1.0)	22.3	22.3	(−0.2)	15.1	15.3	(1.4)	14.5	14.7	(1.1)
200	15.9	15.8	(−0.6)	22.8	22.9	(0.2)	16.0	16.2	(1.4)	15.4	15.6	(1.2)
250	16.8	16.7	(−0.3)	23.3	23.4	(0.4)	16.9	17.1	(1.3)	16.4	16.5	(1.2)
300	17.6	17.6	(0.0)	23.7	23.8	(0.4)	17.8	18.0	(1.1)	17.3	17.5	(1.1)
350	18.5	18.6	(0.3)	24.1	24.2	(0.4)	18.7	18.9	(0.8)	18.2	18.4	(1.0)
400	19.4	19.5	(0.5)	24.4	24.5	(0.2)	19.7	19.8	(0.4)	19.1	19.3	(0.9)
450	20.3	20.4	(0.7)	24.7	24.6	(−0.1)	20.7	20.7	(0.0)	20.1	20.3	(0.8)
500	21.2	21.4	(1.0)	24.9	24.7	(−0.6)	21.7	21.6	(−0.5)	21.1	21.2	(0.6)

long-bar technique to provide results having a similar uncertainty level at the higher temperatures.

5.2 *Consistency of bar stock*

Table 3 contains a summary of the results of measurements by the standard long-bar method on specimens from each end of the bar stock for each of the four materials. (The sample ends were marked A and E with the preface 2 for the 50 mm diameter samples and with the designations S, I, N, and ZS for the 310 stainless steel, Inconel 600, Nimonic 75, and 430 stainless steel, respectively). Table 4 provides a similar summary for thermal diffusivity measurements.

Table 3. Comparison of thermal conductivity (measured with the long-bar apparatus) of each material cut from the ends of the 25 mm diameter bar stock. Percentage difference (%diff) between the results obtained is shown in parentheses.

θ/°C	Thermal conductivity/W m^{-1} K^{-1}											
	310 stainless steel			430 stainless steel			Iconel 600			Nimonic 75		
	S-A	S-E	%diff	ZS-A	ZS-E	%diff	I-A	I-E	%diff	N-A	N-E	%diff
100	14.1	14.3	(1.0)	21.7	21.6	(−0.6)	14.2	14.2	(0.0)	13.6	13.6	(−0.4)
200	15.9	16.0	(0.8)	22.8	22.8	(−0.3)	16.0	15.9	(−0.2)	15.4	15.3	(−1.0)
300	17.6	17.8	(0.7)	23.7	23.8	(0.0)	17.8	17.7	(−0.2)	17.3	17.1	(−1.1)
400	19.4	19.5	(0.6)	24.4	24.5	(0.3)	19.7	19.7	(−0.1)	19.1	19.0	(−0.9)
500	21.2	21.3	(0.5)	24.9	25.0	(0.5)	21.7	21.7	(0.2)	21.1	21.0	(−0.3)
600	22.9	23.0	(0.4)	24.2	24.9	(2.7)	23.7	23.8	(0.5)	23.0	23.1	(0.4)
700	24.7	24.8	(0.3)	26.0	25.8	(−0.6)	25.9	26.1	(0.9)	25.0	25.3	(1.2)

The average differences over the complete temperature range are within ±1% for measured thermal conductivity and ±1.5% for thermal diffusivity. These differences are insignificant when compared with the estimated uncertainties of ±4% for the methods and they indicate clearly that the bar stocks are homogenous and reproducible throughout.

5.3 *Batch-to-batch consistency*

Measurements of thermal conductivity with the short-sample apparatus on specimens of three materials cut from 25 mm and 50 mm diameter bar stocks were undertaken

Table 4. Comparison of thermal diffusivity (measured by the laser-flash method) of each material cut from the ends of the 25 mm diameter bar stock. Percentage difference (%diff) between the results obtained is shown in parentheses.

θ/°C	a/cm^2 s^{-1}											
	310 stainless steel			430 stainless steel			Iconel 600			Nimonic 75		
	S-A	S-E	%diff	ZS-A	ZS-E	%diff	I-A	I-E	%diff	N-A	N-E	%diff
100	0.039	0.038	(−2.2)	0.055	0.056	(2.1)	0.037	0.037	(−1.8)	0.036	0.035	(−5.1)
200	0.042	0.042	(0.0)	0.055	0.056	(1.6)	0.041	0.041	(−1.8)	0.039	0.038	(−2.4)
300	0.045	0.045	(1.5)	0.053	0.054	(1.4)	0.045	0.044	(−1.7)	0.042	0.042	(−0.7)
400	0.047	0.048	(2.3)	0.050	0.051	(1.4)	0.048	0.047	(−1.5)	0.045	0.045	(0.3)
500	0.049	0.051	(2.7)	0.045	0.046	(1.8)	0.051	0.050	(−1.3)	0.047	0.048	(0.9)
600	0.051	0.053	(2.6)	0.039	0.040	(2.7)	0.053	0.053	(−1.0)	0.049	0.050	(1.0)
700	0.053	0.054	(2.2)	0.042	0.042	(0.0)	0.055	0.055	(−0.7)	0.051	0.052	(0.7)
800	0.055	0.056	(1.5)	0.049	0.051	(3.1)	0.057	0.057	(−0.3)	0.053	0.053	(0.2)
900	0.056	0.056	(0.4)	0.053	0.054	(2.0)	0.059	0.059	(0.1)	0.055	0.055	(−0.7)

Table 5. Thermal conductivity of 310 stainless steel (i) measured with the long bar (LB) and short-sample (SSA) apparatuses, (ii) for different diameters, and (iii) results with time; and electrical resistivity of specimens with different diameters. Percentage difference (%diff) between the results obtained is shown in parentheses.

θ/°C	λ/W m^{-1} K^{-1}		ρ/10$^7\Omega$ m			λ/W m^{-1} K^{-1}				
	S-A					2S-A2				%diff LB to combined 2S-A2
	LB	SSA	S-A	2S-A2	%diff	(12/88)	(01/89)	(02/89)	combined	
50	13.2	13.0	8.93	9.18	(−2.8)	12.8	12.9	13.0	12.9	(2.6)
100	14.1	13.9	9.23	9.47	(−2.7)	13.7	13.7	13.8	13.7	(2.7)
200	15.9	15.8	9.78	10.01	(−2.4)	15.3	15.5	15.5	15.4	(2.8)
300	17.6	17.6	10.27	10.49	(−2.2)	17.0	17.3	17.1	17.1	(2.9)
400	19.4	19.5	10.70	10.91	(−2.0)	18.7	19.0	18.8	18.8	(3.0)
500	21.2	21.4	11.07	11.28	(−1.9)	20.3	20.8	20.5	20.5	(3.1)
600	22.9	–	11.38	11.58	(−1.7)	–	–	–	–	–
700	24.7	–	11.64	11.83	(−1.6)	–	–	–	–	–
800	–	–	11.83	12.01	(−1.5)	–	–	–	–	–

and compared with values of electrical resistivity as well as with thermal conductivity measured at different times. The latter measurements were used to investigate any possible aging effects that may occur with time. The results are shown in tables 5 – 7.

The results indicate that there are small but consistent differences in thermal conductivity between the specimens cut from 25 mm and 50 mm diameter stocks. In all cases the value for the 50 mm stock is lower than that for the 25 mm material ranging from approximately 2% to 3.5% overall. However, it should be noted that, particularly for 310 stainless steel and Inconel 600, there are corresponding small differences in the electrical resistivity of the order 1% to 3%. For each of the materials, these values are higher than those for the 25 mm stock. Therefore it would appear that, while the differences are real, overall they are well within the experimental uncertainties and the stocks can be considered to be practically identical so that the combined results are representative of the stock material at either diameter.

Table 6. Thermal conductivity of Inconel 600 (i) measured with the long bar (LB) and short-sample (SSA) apparatuses, (ii) for different diameters, and (iii) results with time; and electrical resistivity of specimens with different diameters. Percentage difference (%diff) between the results obtained is shown in parentheses.

$\theta/°C$	$\lambda/W\ m^{-1}\ K^{-1}$		$\rho/10^7 \Omega\ m$			$\lambda/W\ m^{-1}\ K^{-1}$				
	I-A					2I-A2				%diff LB to combined
	LB	SSA	I-A	2I-A2	%diff	(12/88)	(01/89)	(02/89)	combined	2I-A2
50	13.4	13.5	10.96	11.18	(−2.0)	13.0	12.9	13.0	13.0	(3.1)
100	14.2	14.4	11.01	11.24	(−2.1)	13.8	13.8	13.9	13.8	(2.7)
200	16.0	16.2	11.11	11.35	(−2.2)	15.4	15.6	15.7	15.6	(2.4)
300	17.8	18.0	11.19	11.44	(−2.2)	17.1	17.4	17.5	17.3	(2.5)
400	19.7	19.8	11.26	11.52	(−2.3)	18.8	19.2	19.3	19.1	(2.9)
500	21.7	21.6	11.32	11.58	(−2.3)	20.5	21.0	21.2	20.9	(3.5)
600	23.7	–	11.37	11.63	(−2.3)	–	–	–	–	–
700	25.9	–	11.41	11.67	(−2.3)	–	–	–	–	–
800	–	–	11.44	11.69	(−2.2)	–	–	–	–	–

Table 7. Thermal conductivity of Nimonic 75 (i) measured with the long bar (LB) and short-sample (SSA) apparatuses, (ii) for different diameters, and (iii) results with tine; and electrical resistivity of specimens with different diameters. Percentage difference (%diff) between the results obtained is shown in parentheses.

$\theta/°C$	$\lambda/W\ m^{-1}\ K^{-1}$		$\rho/10^7 \Omega\ m$			$\lambda/W\ m^{-1}\ K^{-1}$			
	N-A					2N-A2			%diff LB to combined
	LB	SSA	N-A	2N-A2	%diff	(12/88)	(01/89)	combined	2N-A2
50	12.8	12.9	11.33	11.36	(−0.3)	12.5	12.4	12.5	(2.3)
100	13.6	13.8	11.40	11.43	(−0.2)	13.4	13.3	13.3	(2.2)
200	15.4	15.6	11.53	11.55	(−0.2)	15.2	15.0	15.1	(2.2)
300	17.3	17.5	11.62	11.65	(−0.2)	17.0	16.8	16.9	(2.0)
400	19.1	19.3	11.68	11.72	(−0.3)	18.9	18.6	18.8	(1.9)
500	21.1	21.2	11.72	11.77	(−0.4)	20.9	20.5	20.7	(1.8)
600	23.0	–	11.72	11.79	(−0.6)	–	–	–	–
700	25.0	–	11.69	11.78	(−0.8)	–	–	–	–
800	–	–	11.63	11.75	(−1.1)	–	–	–	–

The measurements over two to three months indicate that during this period there are no effects of aging on any of the materials, which is a further advantage for a standard reference material.

5.4 *Derivation of thermal conductivity*

This comprehensive series of measurements of individual properties of these materials also allows investigation of the differences between measured values and those obtained by indirect measurement or calculation. The measurements of thermal expansivity provide information not only to correct measured values of thermal conductivity and thermal diffusivity, but also to correct for density thereby allowing derivation of thermal conductivity from thermal diffusivity, specific heat capacity, and density.

Results of the measurement of electrical resistivity can be used to calculate thermal conductivity from an empirical modified Wiedemann–Franz relationship (Smith and Palmer 1935) of the form:

$$\lambda = L(T/\rho) + C\,,$$

Table 8. Values of L and C for use in the modified Wiedemann – Franz equation.

System	$L/10^8(\mathrm{V\ K^{-1}})^2$	$C/\mathrm{W\ m^{-1}\ K^{-1}}$	Approximate accuracy/%
Ferritic steels	2.43	9.2	8
Austenitic steels	2.39	4.2	8
Nickel – chromium alloys	2.20	6.0	6

Table 9. Summarised thermophysical property data for 310 stainless steel.

$\theta/°\mathrm{C}$	$\frac{\mathrm{d}L}{L}\Big/\%$	$d/\mathrm{g\ cm^{-3}}$	$C_p/\mathrm{J\ g^{-1}\ K^{-1}}$	$a/\mathrm{cm^2\ s^{-1}}$ calculated $a = \lambda/dC_p$	$a/\mathrm{cm^2\ s^{-1}}$ measured	$a/\mathrm{cm^2\ s^{-1}}$ *corrected*
20	0.00	7.88	–	–	–	–
50	0.04	7.87	0.480	0.035	0.037	*0.037*
100	0.11	7.86	0.493	0.036	0.039	*0.039*
150	0.19	7.84	0.510	0.038	0.040	*0.040*
200	0.27	7.82	0.520	0.039	0.042	*0.042*
250	0.36	7.80	0.529	0.041	0.043	*0.044*
300	0.45	7.78	0.535	0.042	0.045	*0.045*
350	0.54	7.76	0.544	0.044	0.046	*0.047*
400	0.63	7.74	0.550	0.046	0.048	*0.048*
450	0.71	7.71	0.558	0.047	0.049	*0.049*
500	0.80	7.69	0.566	0.049	0.050	*0.050*
550	0.89	7.67	0.574	0.050	0.051	*0.051*
600	0.96	7.66	0.596	0.050	0.052	*0.053*
650	1.08	7.63	0.601	0.052	0.053	*0.054*
700	1.17	7.61	0.613	0.053	0.054	*0.054*
750	1.27	7.59	0.614	0.055	0.055	*0.055*
800	1.37	7.57	0.622	–	0.055	*0.056*
850	1.46	7.55	0.623	–	0.056	*0.057*
900	1.56	7.52	0.623	–	0.056	*0.057*

$\theta/°\mathrm{C}$	$\frac{\mathrm{d}L}{L}\Big/\%$	$d/\mathrm{g\ cm^{-3}}$	$C_p/\mathrm{J\ g^{-1}\ K^{-1}}$	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ calculated from ρ	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ calculated $\lambda = adC_p$	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ measured	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ *corrected*
20	0.00	7.88	–	12.2	–	12.7	–
50	0.04	7.87	0.480	12.8	13.9	13.2	*13.2*
100	0.11	7.86	0.493	13.9	14.9	14.1	*14.1*
150	0.19	7.84	0.510	14.8	16.1	15.0	*15.0*
200	0.27	7.82	0.520	15.8	17.0	15.9	*15.9*
250	0.36	7.80	0.529	16.7	17.9	16.8	*16.8*
300	0.45	7.78	0.535	17.5	18.7	17.7	*17.8*
350	0.54	7.76	0.544	18.4	19.5	18.6	*18.7*
400	0.63	7.74	0.550	19.2	20.2	19.5	*19.6*
450	0.71	7.71	0.558	20.1	21.0	20.4	*20.5*
500	0.80	7.69	0.566	20.9	21.8	21.2	*21.4*
550	0.89	7.67	0.574	21.7	22.5	22.1	*22.3*
600	0.96	7.66	0.596	22.5	23.7	23.0	*23.2*
650	1.08	7.63	0.601	23.4	24.3	23.9	*24.2*
700	1.17	7.61	0.613	24.2	25.1	24.8	*25.1*
750	1.27	7.59	0.614	25.0	25.4	25.7	*26.0*
800	1.37	7.57	0.622	25.9	26.0	–	–
850	1.46	7.55	0.623	–	26.2	–	–
900	1.56	7.52	0.623	–	26.4	–	–

Table 10. Summarised thermophysical property data for Inconel 600.

$\theta/°C$	$\frac{dL}{L}/\%$	$d/g\ cm^{-3}$	$C_p/J\ g^{-1}\ K^{-1}$	$a/cm^2\ s^{-1}$ calculated $a = \lambda/dC_p$	$a/cm^2\ s^{-1}$ measured	$a/cm^2\ s^{-1}$ *corrected*
20	0.00	8.40	–	–	–	–
50	0.03	8.39	0.451	0.035	0.035	*0.035*
100	0.09	8.37	0.467	0.036	0.037	*0.037*
150	0.15	8.36	0.481	0.037	0.039	*0.039*
200	0.22	8.34	0.491	0.039	0.041	*0.041*
250	0.29	8.32	0.501	0.040	0.043	*0.043*
300	0.37	8.30	0.509	0.042	0.044	*0.045*
350	0.45	8.28	0.514	0.044	0.046	*0.046*
400	0.52	8.27	0.522	0.046	0.048	*0.048*
450	0.60	8.25	0.528	0.047	0.049	*0.049*
500	0.67	8.23	0.533	0.049	0.051	*0.051*
550	0.75	8.21	0.541	0.051	0.052	*0.052*
600	0.83	8.19	0.591	0.049	0.053	*0.054*
650	0.91	8.17	0.592	0.051	0.054	*0.055*
700	1.00	8.15	0.597	0.053	0.055	*0.056*
750	1.09	8.13	0.600	0.055	0.056	*0.057*
800	1.18	8.10	0.602	–	0.057	*0.058*
850	1.27	8.08	0.606	–	0.058	*0.059*
900	1.36	8.06	0.611	–	0.059	*0.060*

$\theta/°C$	$\frac{dL}{L}/\%$	$d/g\ cm^{-3}$	$C_p/J\ g^{-1}\ K^{-1}$	$\lambda/W\ m^{-1}\ K^{-1}$ calculated from ρ	$\lambda/W\ m^{-1}\ K^{-1}$ calculated $\lambda = adC_p$	$\lambda/W\ m^{-1}\ K^{-1}$ measured	$\lambda/W\ m^{-1}\ K^{-1}$ *corrected*
20	0.00	8.40	–	11.9	–	12.8	–
50	0.03	8.39	0.451	12.5	13.3	13.3	*13.3*
100	0.09	8.37	0.467	13.5	14.5	14.2	*14.2*
150	0.15	8.36	0.481	14.4	15.7	15.0	*15.1*
200	0.22	8.34	0.491	15.4	16.7	15.9	*16.0*
250	0.29	8.32	0.501	16.3	17.8	16.8	*16.9*
300	0.37	8.30	0.509	17.3	18.8	17.8	*17.8*
350	0.45	8.28	0.514	18.2	19.6	18.7	*18.8*
400	0.52	8.27	0.522	19.1	20.6	19.7	*19.8*
450	0.60	8.25	0.528	20.1	21.4	20.7	*20.8*
500	0.67	8.23	0.533	21.0	22.2	21.7	*21.8*
550	0.75	8.21	0.541	22.0	23.0	22.7	*22.8*
600	0.83	8.19	0.591	22.9	25.7	23.7	*23.9*
650	0.91	8.17	0.592	23.8	26.2	24.8	*25.0*
700	1.00	8.15	0.597	24.8	26.9	25.8	*26.1*
750	1.09	8.13	0.600	25.7	27.4	26.9	*27.2*
800	1.18	8.10	0.602	26.6	27.9	–	–
850	1.27	8.08	0.606	–	28.4	–	–
900	1.36	8.06	0.611	–	29.0	–	–

where L is a modified Lorenz number for the electronic component and C is a constant which represents all contributions other than those due to electrons, also with the assumption that they do not vary with temperature.

Over a number of years Powell and colleagues (Powell and Hickman 1946; Powell 1952) investigated a number of alloys including those based on iron (both austenitic and ferritic steels) and also nickel–chromium alloys (Inconels and Nimonic) (Powell and Tye 1960, 1967) and provided values for L and C. These are shown in table 8 together with their estimated accuracies for each equation.

Table 11. Summarised thermophysical property data for Nimonic 75.

$\theta/°C$	$\frac{dL}{L}\Big/\%$	$d/\mathrm{g\ cm^{-3}}$	$C_p/\mathrm{J\ g^{-1}\ K^{-1}}$	$a/\mathrm{cm^2\ s^{-1}}$ calculated $a = \lambda/dC_p$	$a/\mathrm{cm^2\ s^{-1}}$ measured	$a/\mathrm{cm^2\ s^{-1}}$ *corrected*
20	0.00	8.36	–	–	–	–
50	0.03	8.35	0.453	0.034	0.034	*0.034*
100	0.09	8.33	0.468	0.035	0.036	*0.036*
150	0.15	8.32	0.480	0.036	0.037	*0.037*
200	0.22	8.30	0.490	0.038	0.039	*0.039*
250	0.30	8.28	0.499	0.039	0.041	*0.041*
300	0.37	8.26	0.507	0.041	0.042	*0.042*
350	0.45	8.24	0.515	0.043	0.043	*0.044*
400	0.53	8.22	0.522	0.045	0.045	*0.045*
450	0.61	8.20	0.531	0.046	0.046	*0.046*
500	0.69	8.18	0.533	0.048	0.047	*0.048*
550	0.77	8.16	0.546	0.049	0.049	*0.049*
600	0.86	8.14	0.603	0.047	0.050	*0.050*
650	0.95	8.12	0.599	0.050	0.051	*0.051*
700	1.05	8.10	0.603	0.052	0.052	*0.052*
750	1.14	8.08	0.610	0.053	0.052	*0.053*
800	1.24	8.05	0.614	–	0.053	*0.054*
850	1.34	8.03	0.615	–	0.054	*0.055*
900	1.44	8.01	0.617	–	0.055	*0.056*

$\theta/°C$	$\frac{dL}{L}\Big/\%$	$d/\mathrm{g\ cm^{-3}}$	$C_p/\mathrm{J\ g^{-1}\ K^{-1}}$	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ calculated from ρ	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ calculated $\lambda = adC_p$	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ measured	$\lambda/\mathrm{W\ m^{-1}\ K^{-1}}$ *corrected*
20	0.00	8.36	–	11.7	–	12.3	–
50	0.03	8.35	0.453	12.3	12.8	12.8	*12.8*
100	0.09	8.33	0.468	13.2	13.9	13.6	*13.7*
150	0.15	8.32	0.480	14.1	14.9	14.5	*14.5*
200	0.22	8.30	0.490	15.0	15.8	15.4	*15.4*
250	0.30	8.28	0.499	15.9	16.7	16.3	*16.4*
300	0.37	8.26	0.507	16.9	17.6	17.2	*17.3*
350	0.45	8.24	0.515	17.8	18.4	18.2	*18.2*
400	0.53	8.22	0.522	18.7	19.2	19.1	*19.2*
450	0.61	8.20	0.531	19.6	20.1	20.1	*20.2*
500	0.69	8.18	0.533	20.5	20.7	21.1	*21.2*
550	0.77	8.16	0.546	21.5	21.6	22.1	*22.2*
600	0.86	8.14	0.603	22.4	24.3	23.1	*23.3*
650	0.95	8.12	0.599	23.3	24.6	24.1	*24.3*
700	1.05	8.10	0.603	24.3	25.2	25.2	*25.4*
750	1.14	8.08	0.610	25.3	25.9	26.2	*26.5*
800	1.24	8.05	0.614	26.3	26.4	27.3	–
850	1.34	8.03	0.615	–	26.7	28.4	–
900	1.44	8.01	0.617	–	27.0	–	–

Values of thermal conductivity at regular temperature intervals were calculated for each material by using the measured electrical resistivity. The results shown in tables 9 to 12 confirmed the value of such equations in that all of the values obtained by this technique agreed with directly measured values. For the four materials, the largest deviation occurred for the nickel–chromium systems at temperatures in the range 550 °C to 650 °C where phase changes occur. In general, calculated values agreed to within ±5% with experimental values for all materials. The calculations have also confirmed that the 310 stainless steel is an austenitic alloy and the 430 stainless steel is ferritic.

Table 12. Summarised thermophysical property data for 430 stainless steel.

$\theta/°C$	$d/g\ cm^{-3}$	$C_p/J\ g^{-1}\ K^{-1}$	$a/cm^2\ s^{-1}$		$\lambda/W\ m^{-1}\ K^{-1}$		
			calculated $a = \lambda/dC_p$	measured	calculated from ρ	calculated $\lambda = adC_p$	measured
20	7.67	–	–	–	17.5	–	20.5
50	7.67	0.477	0.057	0.055	20.3	20.0	20.9
100	7.67	0.498	0.057	0.055	21.5	21.1	21.6
150	7.67	0.516	0.056	0.055	22.5	21.9	22.3
200	7.67	0.538	0.055	0.055	23.4	22.8	22.8
250	7.67	0.561	0.054	0.055	24.2	23.5	23.3
300	7.67	0.580	0.053	0.054	24.9	23.8	23.8
350	7.67	0.605	0.052	0.052	25.6	24.2	24.1
400	7.67	0.633	0.050	0.050	26.3	24.4	24.5
450	7.67	0.662	0.049	0.048	26.9	24.5	24.7
500	7.67	0.718	0.045	0.046	27.5	25.1	24.9
550	7.67	0.793	–	0.043	28.1	25.9	–
600	7.67	0.850	0.038	0.039	28.6	25.5	24.5
650	7.67	0.945	0.035	–	29.2	–	25.3
700	7.67	0.830	0.041	0.042	29.9	26.9	25.9
750	7.67	0.747	0.046	0.047	30.5	26.8	26.4
800	7.67	–	–	0.050	31.2	–	26.7
850	7.67	–	–	0.053	32.0	–	–
900	7.67	–	–	0.054	–	–	–

Table 13. Equations representing reference values for thermal conductivity of the four materials.

Material	Equation	Temperature range, $\Delta\theta/°C$
310 stainless steel	$\lambda = 12.338 + 1.781 \times 10^{-2}\,\theta$	50–750
430 stainless steel	$\lambda = 20.159 + 1.589 \times 10^{-2}\,\theta - 1.283 \times 10^{-5}\,\theta^2$	50–500
Inconel 600	$\lambda = 12.479 + 1.648 \times 10^{-2}\,\theta + 3.741 \times 10^{-6}\,\theta^2$	50–750
Nimonic 75	$\lambda = 11.958 + 1.657 \times 10^{-2}\,\theta + 3.252 \times 10^{-6}\,\theta^2$	50–750

The derivation of thermal conductivity from thermal diffusivity indicates clearly that this is valid for the four materials, which can also be seen in tables 9 to 12. In all cases the values agree with the measured values to well within the levels of uncertainty based on the known levels for the individual properties.

The 430 stainless steel and the two nickel–chromium alloys have uncertainty values at the higher end of the range, but only at temperatures over the respective temperature ranges where phase transitions are known to occur. While the two nickel–chromium alloys exhibit a significant change in specific heat capacity in the 550 °C to 650 °C range, no such behaviour can be seen for the 430 stainless steel. It should be noted that a small but significant drop (approximately 3% to 4%) in thermal conductivity at 600 °C was measured (and was reproducible), whereas no significant changes in specific heat capacity or electrical resistivity were found. However, measurements of thermal diffusivity at or close to 600 °C gave values having a wide variation such that no definitive value could be obtained. As a result of this uncertain behaviour, above 500 °C reference values are provided only for the range 50 °C to 500 °C until this anomalous behaviour has been studied in more detail.

6 Collected results

Tables 9 to 12 contain the summarised results of all experimental, corrected (for thermal expansion), and calculated values for the thermal properties of the four materials. Equations representing reference values provided for both the experimentally measured and corrected values of thermal conductivity are given in table 13. These have been provided since use of the properties varies among workers in the field.

In general, most people use uncorrected values when comparing results of measurements. For most materials correction for thermal expansion only becomes significant at higher temperatures and only exceeds 1% to 3% when the thermal expansion is much higher than those in this investigation.

For each material reference values for the uncorrected thermal conductivity can be represented by appropriate equations to provide values having an uncertainty of $\pm 4\%$, as shown in table 13.

7 Summary

A comprehensive series of thermophysical properties measurements have been carried out on four alloys proposed as candidate reference materials for the temperature range 50 °C to 750 °C. As a result of the investigations, reference values for thermal conductivity and thermal diffusivity are recommended for 310 stainless steel, Nimonic 75, and Inconel 600 alloys over the complete temperature range and for 430 stainless steel up to 500 °C. Supplies of each material are available from the National Physical Laboratory from stocks of three different diameters.

Work is ongoing to provide reference data on several other materials, including molybdenum, BSC iron, and a titanium–aluminium–vanadium alloy, to provide a series of such reference materials covering a range of thermal conductivity from about 8 W m^{-1} K^{-1} to 200 W m^{-1} K^{-1}.

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