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Radiance Temperatures (in the Wavelength Range 530 to 1500 nm) of Nickel at Its Melting Point by a Pulse-Heating Technique[1]

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ABSTRACT

The radiance temperatures (at seven wavelengths in the range 530 to 1500 nm) of nickel at its melting point were measured by a pulse-heating technique. The method is based on rapid resistive self-heating of the specimen from room temperature to its melting point in less than 1s and on simultaneously measuring specimen radiance temperatures every 0.5 ms. Melting of the specimen was manifested by a plateau in the radiance temperature-vs-time function for each wavelength. The melting-point radiance temperatures for a given specimen were determined by averaging the measured temperatures along the plateau at each wavelength. The melting-point radiance temperatures for nickel, as determined by averaging the results for at each wavelength for 25 specimens, are: 1641 K at 530 nm, 1615 K at 627 nm, 1606 K at 657 nm, 1589 K at 722 nm, 1564 K at 812 nm, 1538 K at 908 nm, and 1381 K at 1500 nm. Based on uncertainties arising from pyrometry and specimen conditions, the combined uncertainty (two standard-deviation level) is about ±6 K for the reported values in the range 530 to 900 nm and is about ±8 K for the reported value at 1500 nm.

KEY WORDS: emissivity (normal spectral); high-speed pyrometry; high temperature fixed points; melting; pyrometry; nickel; radiance temperature.

1. INTRODUCTION

In the last two decades, extended measurements of the radiance temperature[5] at the melting point of selected pure metals in the wavelength range 500 to 1000 nm have been made at the National Institute of Standards and Technology (NIST) in the United States and at the Istituto de Metrologia 'G. Colonnetti' (IMGC) in Italy [1]. These measurements have shown that during the initial melting period, the radiance temperature at each wavelength is essentially constant and very reproducible for different specimens of a given metal. Recent work at NIST has extended melting-point radiance temperature measurements to metals with lower melting points [2, 3] and to a longer wavelength, 1500 nm [4, 5]. In the present paper, we describe similar measurements made on nickel in the wavelength range 530 to 1500 nm.

The measurement technique is based on rapid resistive self-heating of a specimen (strip shaped) from room temperature to its melting point in less than one second by passing a large electrical current pulse through the specimen. As the specimen heats, its radiance temperature at each of seven wavelengths (nominally between 500 and 1500 nm) is measured by two pyrometers every 0.5 ms. Radiances at each of six wavelengths in the nominal range 500 nm to 900 nm are measured with a high-speed six-wavelength pyrometer viewing a surface of the specimen. Radiances at two wavelengths, nominally 650 nm and 1500 nm, are measured by a high-speed two-wavelength pyrometer viewing a surface of the specimen. The melting-point radiance temperatures for a given specimen of nickel were determined by averaging the measured radiance temperatures along the melting plateau for each wavelength. All temperatures reported in this paper, except where explicitly noted otherwise, are based on the International Temperature Scale of 1990 (ITS-90) [6].

Details concerning the design and construction of the pulse-heating system [7, 8] and the design, operation, and calibration of the six-wavelength pyrometer [9] are given in the cited publications.

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[5] **Radiance temperature (sometimes referred to as brightness temperature) of the specimen surface at a given wavelength is the temperature at which a blackbody at the same wavelength has the same radiance as the surface. The wavelength is the effective wavelength of the measuring pyrometer.**

The 650 nm channel of the two-wavelength pyrometer is used in the calibration of the 1500 nm channel and it is used as a control to compare its results to that of the similar wavelength of the six-wavelength pyrometer. Details concerning the calibration and operation of the two-wavelength pyrometer are given in eariler publications [4, 5].

2. MEASUREMENTS

Measurements of the radiance temperature of nickel at its melting point were performed on 25 specimens in the form of strips cut from 50 x 50 mm sheets of 99.98% nickel. Eighteen specimens were used with the six-wavelength pyrometer and seven specimens were used with the two-wavelength pyrometer. A typical analysis of the nickel material used to fabricate the sheets, as reported by the manufacturer, yielded the following impurities in ppm by weight: C, 70; Cu, Fe, Mg, Mn, Ti, and S, 10; Co, Cr and Si, 8. The nominal dimensions of each specimen strip were: length 50 mm, width 3 mm, and thickness 0.25 mm. The surfaces of 19 of the specimens (including all specimens used with the two-wavelength pyrometer) were mechanically abraded with sandpaper to remove possible surface contaminants and 6 specimens were used in "as received" condition. Each experiment was performed with the nickel strip in an argon gas environment (approximately 0.15 MPa) to minimize contamination of the specimen surface at high temperatures. The duration of the electrical current pulse, used to heat each specimen from room temperature to its melting temperature, ranged from approximately 390 to 760 ms.

Figure 1 shows typical radiance-temperature data at and near the melting point of nickel at two wavelengths (657 and 1500 nm) obtained with the pyrometers during pulse-heating experiments. The melting of the specimen is manifested by a plateau region in the measured radiance temperature results for each wavelength. The flat region along each plateau (indicated by the dashed line) was used to determine the melting radiance temperature at each wavelength. Except for the results at 530 nm which were noisy due to the very low radiance at this wavelength, the radiance temperature along the flat region of each plateau was essentially constant within a range of

less than ± 1 K for all specimens. The effective wavelength for each pyrometer channel was determined from the respective average radiance temperature using the method of Kostkowski and Lee [10].

3. RESULTS

For each nickel specimen, the radiance temperature at the melting point was determined at each wavelength by averaging the measured temperatures along the flat portion of the corresponding plateau (indicated by the dashed line in Fig.1). The number of temperatures used for averaging ranged from 35 to 121, depending upon the heating rate and the behavior of the specimen during melting. The standard deviation of an individual plateau radiance temperature from the average obtained for that specimen was in the range 0.1 to 1.2 K with the largest deviations in the 530 nm results. When the results at 530 nm are ignored, the largest standard deviation of an individual point from the specimen average is only 0.3 K, indicating the smooth behavior of the melting plateau of each specimen at each wavelength. The trend (or slope) of radiance temperature along each plateau was determined by fitting a linear function in time to the measured radiance temperatures using the least squares method. The slope of the linear function for all experiments on nickel was in the range -30 to 39 $K\cdot s^{-1}$. The temperature difference between the beginning and end of the plateau, as determined from this slope, was in the range -0.8 to 1.6 K for all experiments (or -0.1 to 0.5 K omitting the 530 nm results). Heating rates for each specimen were determined by fitting a linear function in time to the radiance temperatures measured during the premelting period. The heating rates for the specimens (slopes of the linear functions approximately 25 K below the melting plateau) ranged from 1500 to 5350 $K\cdot s^{-1}$. An examination of the results showed no relationship between heating rate and the measured melting-point radiance temperature. There was also no difference in the results from specimens used "as received" compared to those with surfaces cleaned with sandpaper.

The 650 nm channel of the two-wavelength pyrometer was used as a control to ensure that the

results at 1500 nm could be combined with the results from the six-wavelength pyrometer. When corrected for the small wavelength difference between the two pyrometers, the average melting-point radiance temperatures as measured by both pyrometers at 657 nm differed by less than 0.5 K and it was concluded that the results from both pyrometers could be combined.

Table I presents the final experimental results of the radiance temperature of nickel at its melting point in the wavelength range 530 to 1500 nm. Depending upon wavelength, the standard deviation of an individual average melting temperature from the overall average is in the range from 0.1 to 0.7 K (only 0.1 to 0.3 K if the noisy results from 530 nm are omitted). Also given in Table I are the corresponding values for the normal spectral emissivity of nickel at its melting point. Emissivity was calculated by means of Plank's law using the present results for radiance temperature and the value 1729 K for the melting point of nickel [11].

4. ESTIMATE OF UNCERTAINTIES

The major sources of uncertainty are (i) the calibration and operation of the pyrometer and (ii) the physical/chemical conditions and melting behavior of each specimen. A detailed analysis of magnitudes of the uncertainties from all sources is given in an earlier publication [12]. Specific items in the error analysis (particularly those related to temperature range) were recomputed whenever the present conditions differed from those in the earlier publication. The resultant uncertainty (two standard-deviation level) in the reported values for melting-point radiance temperatures at each of the six wavelengths in the range 530 to 908 nm is estimated to be about ± 6 K and about ± 8 K at 1500 nm.

5. DISCUSSION

Only a few papers that report the radiance temperature of nickel at its melting point were found in the literature. These values from the literature and the present values for the radiance temperatures of nickel at its melting point are listed in Table II and are plotted as functions of wavelength in Fig. 2. All the results, except those of Bonnel et al. [13], are within the combined

experimental uncertainities. The results of Bonnel et al. at 645 nm are about 13 K lower than the interpolated value from the present results. The radiance temperatures computed from the results of Schaefers et al. [14], corrected for the wavelength difference, are about 6 K higher at 547 nm and about 1 K higher at 650 nm. Earlier results obtained at IMGC, also using a pulse heating technique and reported by Cezairliyan et al. [1], differ by less than 1 K at 659 nm and are about 2 K higher at 900 nm. This later comparison shows the high degree of reproducibility that can be achieved using pulse-heating techniques.

Also listed in Table II are values from the literature and the present values for the normal spectral emissivity of nickel at its melting point obtained from melting-point radiance temperature measurements. These emissivity values were obtained by the investigators using Plank's law and reported values for the melting temperature of nickel. To provide a common basis for comparison, the values for normal spectral emissivity were adjusted to a common melting temperature of 1729 K on ITS-90 [11]. The results for normal spectral emissivity are plotted as a function of wavelength in Fig. 3. These results for normal spectral emissivity of nickel at its melting point show a decrease of about 55% over the entire wavelength range of the experiment, 530 to 1500 nm.

The dashed curves in Figs. 2 and 3 represent quadratic functions fitted to the present results using the least-squares method. The functions are of the form:

$$y = a + b\lambda + c\lambda^2 \tag{1}$$

where y is either radiance temperature, T_r in K, or normal spectral emissivity, $\epsilon_{n,\lambda}$, and λ is wavelength in nm. The values for these coefficients are given in Table III.

6. CONCLUSIONS

The present measurements for the melting-point radiance temperatures of nickel have yielded highly reproducible results (within ± 2 K) at seven wavelength in the range 530 to 1500 nm. Ignoring the noisy results at 530 nm, the results at the other wavelengths in this range are within ± 1 K. These results are similar to those found for many other metals [1] and contribute additional data

to suggest that the radiance temperature of selected metals at their melting points can be used as easily realizable temperature standards for high-temperature optical pyrometry. The melting behavior of nickel with its very flat plateau region (illustrated in Fig. 1) and its highly reproducible results identifies it as a very suitable candidate for the establishment of a secondary temperature reference based on its melting-point-radiance temperatures.

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REFERENCES

1. A. Cezairliyan, A.P. Miiller, F. Righini, and A. Rosso, *Temperature: Its Measurement and Control in Science and Industry,* Vol. 6, Part 1, J.F. Schooley, ed. (AIP, New York, 1992), p. 377.
2. A. Cezairliyan, J. L. McClure, and A.P. Miiller, *Int. J. Thermophys.* **15:** 993 (1994).
3. J.L. McClure and A. Cezairliyan, *Int. J. Thermophys.* **18:** 291 (1997).
4. E. Kaschnitz and A. Cezairliyan, *Int. J. Thermophys.* **17:** 1069 (1996).
5. E. Kaschnitz, J.L. McClure, and A. Cezairliyan, *High Temp.- High Press.* 29: xxx (1997).

6.H. Preston-Thomas, *Metrologia* **27**:3 (1990); *Metrologia* **27**:107 (1990).

7. A. Cezairliyan, M.S. Morse, H.A. Berman, C.W. Beckett, *J. Res. Natl. Bur. Stand.* (U.S.) **74A:**65 (1970).
8. A. Cezairliyan, *J. Res. Natl. Bur. Stand. (U.S.)* **75C:**7 (1971).
9. A. Cezairliyan, G.M. Foley, M.S. Morse, and A.P. Miiller, in *Temperature: Its Measurement and Control in Science and Industry*, Vol. 6, Part 2, J.F. Schooley, ed. (AIP, New York 1992), p. 757.
10. H.J. Kostkowski and R.D. Lee, in *Temperature: Its Measurement and Control in Science and Industry*, Vol. 3, Part 1, C.M. Hertzfeld, ed. (Reinhold, New York, 1962), p. 449.

11. A. Cezairliyan and A.P. Miiller, *Int. J. Thermophys.* **5:** 315 (1984).

12. A. Cezairliyan and A.P. Miiller, *Int. J. Thermophys*. **13**:39 (1992).

13. D.W. Bonnell, J.A. Treverton, A.J. Valerga, and J.L. Margrave, in *Temperature: Its Measurement and Control in Science and Industry*, Vol. 4, Part 1, H.H. Plumb, ed. (ISA, Pittsburgh, 1972), p. 483.

14. K. Schaefers, M. Rösner-Kuhn, and M.G. Frohberg , *Int. J. Thermophys.* **16:** 997 (1995).

Table I. Final Results for the Average Radiance Temperature and Normal Spectral Emissivity, at Seven Wavelengths, of Nickel at its Melting Point.

Effective wavelength[a] (nm)	Radiance temp.[b] (K)	Standard dev.[c] (K)	Max.abs. dev. (K)	Norm. spectral emissivity[d]
530	1641.2	0.7	1.4	0.432
627	1614.7	0.1	0.2	0.391
657	1605.8	0.2	0.4	0.378
722	1588.5	0.1	0.3	0.361
812	1563.7	0.1	0.3	0.338
908	1537.8	0.2	0.3	0.320
1500	1381.4	0.3	0.8	0.247

[a] Determined at the respective radiance temperature using the definition of effective wavelength given by Kostkowski and Lee [10].

[b] Average of the specimen melting-point radiance temperatures at each effective wavelength.

[c] Standard deviation of an individual specimen melting-point radiance temperature from the average of values obtained from all specimens.

[d] Determined by means of Planck's law from the average plateau radiance temperature and the value 1729 K (on ITS-90) for the melting point of nickel [11].

Table II. Radiance Temperatures and Normal Spectral Emissivities at Wavelengths (λ) in the Range 530 to 1500 nm of Nickel at its Melting Point as Reported in the Literature.

Investigator	Ref. No.	Year	Purity (mass.%)	Heating method[a]	λ (nm)	Radiance Temperature (K) As reported	Radiance Temperature (K) On ITS-90	Normal Spectral Emissivity As reported	Normal Spectral Emissivity Adjusted for a common M.P.[b]
Bonnell et al.	13	1972	99.8	E	645	1597	1597	0.346	0.344
Cezairliyan et al.	1	1992	99.99	R	659		1605±6		0.377
					900		1541±6		0.324
Schaefers et al.	14	1995		E	547		1642[c]	0.46	0.45
					650		1609[c]	0.395	0.386
Present work			99.98	R	530		1641±6		0.432
					627		1615±6		0.391
					657		1606±6		0.378
					722		1589±6		0.361
					812		1564±6		0.338
					908		1538±6		0.320
					1500		1381±8		0.247

(Table II, continued)

[a] Method used to heat the specimen (specimen geometry in parentheses):

E: electromagnetic levitation/induction heating (sphere)

R: resistive self-heating (strip)

[b] Adjusted values for emissivity are based on the reported melting-point radiance temperatures (on ITS-90) and the melting temperature of 1729 K (on ITS-90) for nickel [11].

[c] Based on the emissivities (0.46 at 547 nm and 0.395 at 650 nm) measured by the investigators and a melting temperature of 1726 K (ITS-90) as reported by the investigators.

Table III. Coefficients of Eq. (1) for Radiance Temperature (T_r) and Normal Spectral Emissivity ($\epsilon_{n,\lambda}$) at the Melting Point for Nickel in the Wavelength Range 530 to 1500 nm.

Coeff	T_r (K)	$\epsilon_{n,\lambda}$
a	1791.0	0.6735
b	-0.28786	-5.650×10^{-4}
c	9.8479×10^{-6}	1.873×10^{-7}
S.D.[a]	0.25	0.005

[a] Standard deviation of an individual point from the curve represented by Eq. (1).

FIGURE CAPTIONS

Fig. 1. Variation of the radiance temperatures of a nickel strip at two representative wavelengths (657 and 1500 nm) just before and during melting as measured with the pyrometers during typical pulse-heating experiments. The effective wavelengths, shown for each channel, were determined following the definition given by Kostkowski and Lee [10]. Each labeled temperature indicates the average melting-point radiance temperature for the experiment computed from the plateau data indicated by the dashed line.

Fig. 2. Comparison (on ITS-90) of literature values and present results for the radiance temperature of nickel at its melting point as a function of wavelength. The dashed line represents the quadratic function, Eq.(1), fitted to the radiance temperature-vs-wavelength data obtained in the present work.

Fig. 3. Variation of the normal spectral emissivity of nickel at its melting point as a function of wavelength. The plotted data correspond to emissivity values adjusted for a common melting temperature of 1729 K [11]. The dashed line represents the quadratic function, Eq.(1), fitted to the normal spectral emissivity vs wavelength data obtained in the present work.

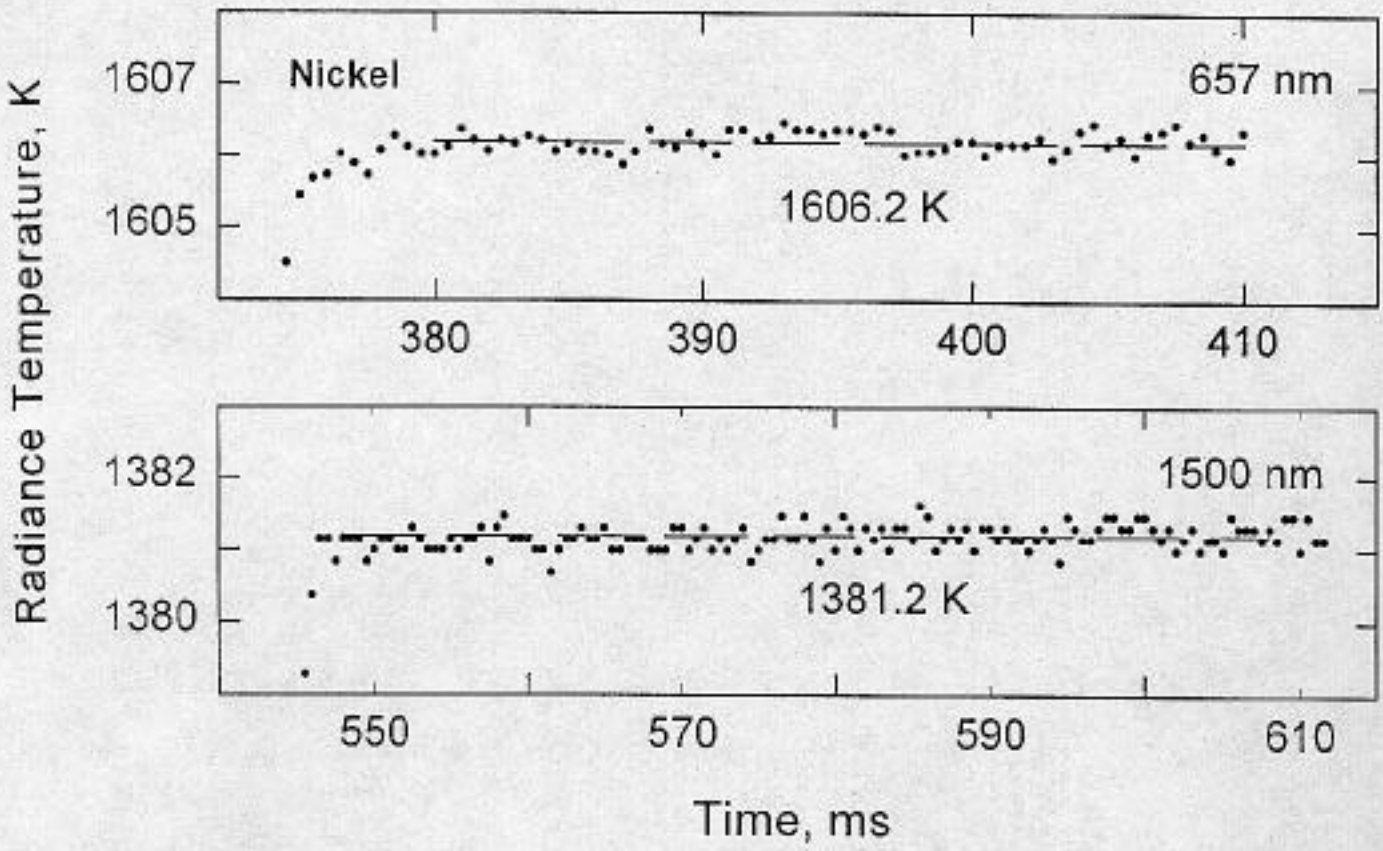
Radiance Temperature, K
1607
1605
Nickel
657 nm
1606.2 K
380
390
400
410
1382
1380
1500 nm
1381.2 K
550
570
590
610
Time, ms

Figure 1

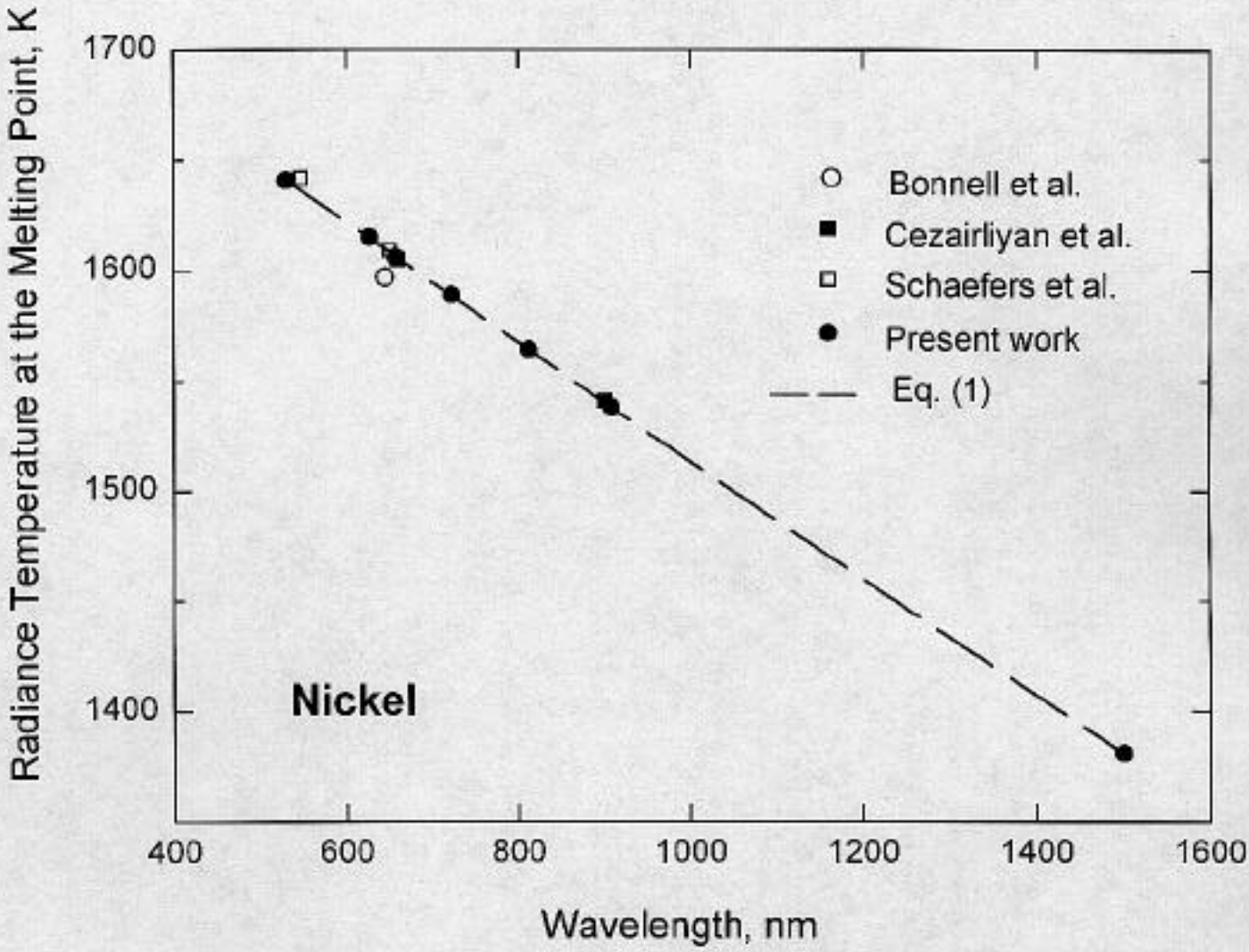
Radiance Temperature at the Melting Point, K
1700
1600
1500
1400
400
600
800
1000
1200
1400
1600
Wavelength, nm
Bonnell et al.
Cezairliyan et al.
Schaefers et al.
Present work
Eq. (1)
Nickel

Figure 2

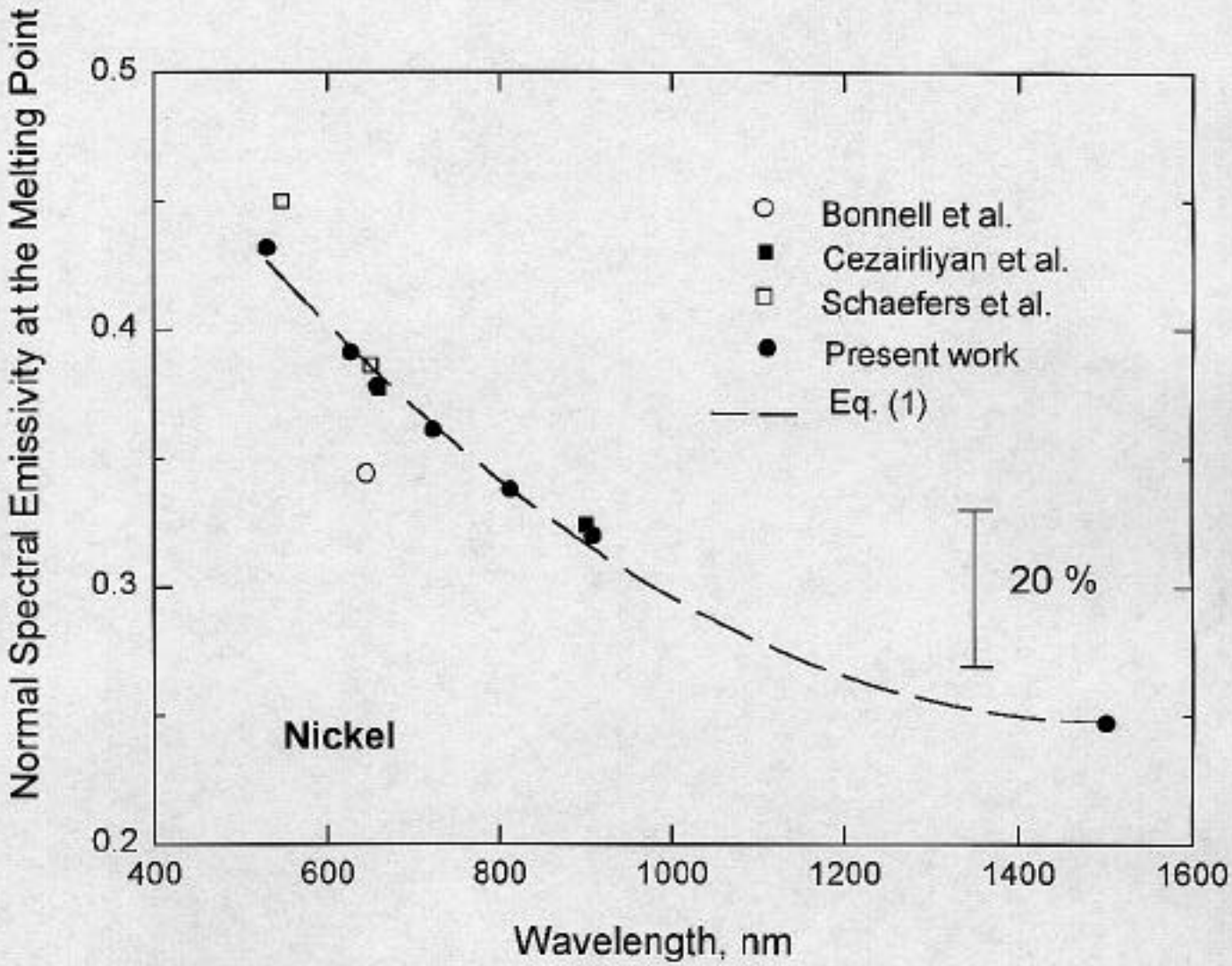
Normal Spectral Emissivity at the Melting Point
0.5
0.4
0.3
0.2
400
600
800
1000
1200
1400
1600
Wavelength, nm
Bonnell et al.
Cezairliyan et al.
Schaefers et al.
Present work
Eq. (1)
20 %
Nickel

Figure 3