A Database of Normal Spectral Emissivities of Metals at High Temperatures[1]

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ABSTRACT

The normal spectral emissivity and its time variation were measured systematically for a total of thirty kinds of pure metals, steels, and alloys at temperatures between 780°C and 1200°C. The spectral data were obtained at about 100 wavelengths continuously from 0.55μm to 5.3μm under different environmental conditions including oxidation. The spectral data were stored in a database with supplementary information on the specimens.

Clear waving of the spectral emissivity with time and wavelength was observed for nickel, Inconel, and SUS444 as surface oxidation progresses while emissivity variations were rather monotonous for other metals such as titanium, cold-rolled steel, and SUS310S. The surface roughness was measured for all specimens by a contact-type instrument before measurements, and it was recorded as supplementary information in the database.

The database was built on an operating system of personal computers to facilitate the dissemination to researchers and engineers interested in the emissivity of metals. Indexes to seek the emissivity data are metal name, wavelength, temperature, time and degree of oxidation represented by an effective thickness of oxide film on the specimen surface.

KEY WORDS: database; high temperature; metal; spectral emissivity; oxidation.

1. INTRODUCTION

It is known that the spectral emissivity of a clean metal surface is low and stable, but it changes drastically when the surface is oxidized. Since the spectral emissivity of metals under oxidation is very important to radiation thermometry, a lot of measurements has been made. There was a comprehensive compilation of spectral emissivity measurements for a variety of metals twenty seven years ago [1]. It was the first and the last big compilation of spectral emissivity trying to include supplementary information on the specimens as widely as possible. The compilation is still very useful even at present, but the data are not complete enough to apply to industrial radiation thermometry. Thus the use of those data is limited to reference information on emissivities because most of the emissivity measurements had been made under unidentified or incomplete conditions, e.g. detailed information on surface roughness and degree of surface oxidation was lacking, and the measurement wavelengths and temperatures were relatively few.

We developed an emissivity measurement system for metals [2], and obtained a large amount of normal spectral emissivity data at nearly continuous wavelengths and temperatures systematically with identified surface roughness to build an emissivity database of metals. The data were described on a standardized format, and the database contents have not only emissivities but also supplementary information on the specimens.

2. MEASUREMENT

2.1. Measurement system

The measurement system and the specimen shape are described in another paper of this volume [2]. The specimen was heated by direct current in a vacuum or oxidizing environments. The normal spectral emissivity was obtained at about 100 wavelengths from 0.55μm to 5.3μm and at temperatures from 780°C to 1200C°.

2.2. Measurement procedure

The average and maximum values of surface roughness were measured for each specimen at the middle of the front surface in the horizontal and vertical directions before the emissivity measurement. The surface roughness meter has a contact-type prove and an analog filter with a cut-off length of 0.8mm.

Several specimens were prepared for each kind of metal, and time variations of the normal spectral emissivity were measured for respective specimens according to three different measurement procedures. The first measurement procedure was such that a specimen was heated from room temperature to a high temperature in a vacuum, and the temperature was varied between 780°C and 1200°C. The vacuum chamber was continuously evacuated by a turbo-molecular pump in this measurement procedure.

The second measurement procedure was such that a specimen was at first heated up to a certain temperature near 1000°C in a vacuum, and then the evacuation valve was closed, and the air or oxygen-added argon gas was introduced into the vacuum chamber at a constant flow rate.

The third procedure was such that a specimen was at first heated at about 600°C or 1000°C in the atmosphere to heavily oxidize the specimen surface before the emissivity measurement. Then the normal spectral emissivity of the specimen was measured at high temperatures in a vacuum according to the same way as the first measurement procedure. Some specimens oxidized according to the second measurement procedure were also used in the third measurement procedure.

An additional measurement procedure was taken for some stainless steel specimens that were heated in the atmosphere with the time variation of temperature simulating an actual

industrial annealing process for stainless steel.

3. DATABASE SYSTEM

3.1. Database operation

The normal spectral emissivity database was at first build on a DOS for Japanese computers, and then it was modified by using Access for Windows95®. Figure 1 shows a data selection form of the database. It is displayed after a selecting a certain kind of metal on the opening form. Figure 1 is an example for nickel among the metals. All measurements for the selected kind of metal are included in the data selection form. When a line on the measurement list is selected on the data selection form, detailed supplementary information on the measurement is displayed; the black line shows the selected measurement that is displayed at the bottom of the form.

Normal spectral emissivity data of the selected measurement can be displayed as a table and graphs according to selections by indexes such as wavelength, time, and temperature. Figure 2 shows an example of displayed graphs when the graph button (emissivity-to-time) and the wavelength of 2.002μm are selected. Three-dimensional graphs of time variations of normal spectral emissivities are also displayed. (They will be shown later in Figure 6 to Figure 9.)

In the cases where measurement data have clear waving of emissivity against time as shown in Figure 2, the degree of oxidation can be represented by an effective thickness of the oxide film on the specimen surface. Figure 3 shows an example of the case. The effective thickness was calculated on the assumption that the emissivity waving was produced by interference of radiation emitted by the metal surface and radiation originally emitted by the metal surface that was successively reflected by the top of the oxide film and the metal surface. When a first valley of emissivity variation occurred at a certain wavelength, the effective thickness was determined as a quarter of the wavelength. The time variation in the effective thickness shown in Figure 3 is the average obtained at several wavelengths. The agreement of effective thicknesses calculated at different wavelengths was actually not very good; the difference was as large as 40% at maximum.

3.2. Database contents

The database has emissivity data from a total of 182 measurements on various metals; titanium, nickel, copper, molybdenum, tungsten, three kinds of cold-rolled steel, four kinds of electromagnetic steel, Inconel 600, Inconel 601, Inconel 625, Kovar, Monel, Nichrome, Permalloy 45, Permalloy 78, three kinds of JIS SUS304 (ANSI304, DIN1.4301), JIS SUS310S (ANSI310S), JIS SUS316, JIS SUS329J2L (NAR DP-3, YUSDX-1, R22CR), JIS SUS430(ANSI430, DIN1.4016), JIS SUS444 (NSS444N, NAR192, YUS190), Ni36 (Invar, Umber), and painted cold-rolled steel.

Since the normal spectral emissivity data obtained in this research are too many to show, only selected emissivity data will be presented as examples in this paper. Figure 4 shows normal spectral emissivities of an as-rolled specimen (a), a polished specimen (b), and abraded specimens ((c), (d), (e)) of electromagnetic steel. The specimens were heated at 1100°C according to the first measurement procedure. The average surface roughness values of the specimens (a), (b), (c), (d) and (e) in the vertical directions were 0.22μm, 0.05μm, 0.05μm, 0.11μm and 0.38μm, respectively. The emissivity of the polished specimen was the lowest, and the emissivities of the abraded specimens had a small variation according to the surface roughness.

Figure 5 shows time variations in the normal spectral emissivities of four specimens of Inconel 601 at the wavelength of 2μm. The specimen surfaces were oxidized with different

oxidizing gases, respectively, at 1000°C according to the second measurement procedure. The average surface roughness values of the specimens (a), (b), (c) and (d) in the vertical directions were 0.25μm, 0.19μm, 0.14μm and 0.11μm, respectively. The metallic color of the specimens was changed to black by oxidation after the measurements. It is seen that a higher oxygen content made a more rapid rise of emissivity.

Figure 6 to Figure 9 show three-dimensional graphs showing time variations of the normal spectral emissivities for JIS SUS444, cold-rolled steel, tungsten and Monel, respectively. The average surface roughness values of the specimens in the vertical directions were 0.05μm, 1.0μm, 0.53μm and 0.43μm, respectively.

Figure 6 shows a time variation in the normal spectral emissivity of a JIS SUS444 specimen when it was heated in a vacuum at 1000°C and then oxidizing gas was introduced according to the second measurement procedure. Clear waving of the emissivity spectrum with wavelength and time is seen as oxidation progresses. It can be concluded that an oxide film grew on the specimen surface, and that it caused interference of emitted radiation in the oxide film. The specimen looked dark green after the emissivity measurement.

Figure 7 shows a time variation in the normal spectral emissivity of a cold-rolled steel specimen when it was heated in a vacuum at 1000°C and then oxidizing gas was introduced according to the second measurement procedure. It is seen that the emissivity increases monotonously as oxidation progresses, and that the emissiviy spectrum finally became relatively flat. It is considered that the oxide film grown on the surface was opaque or scattering which prevented emitted radiation to interfere in the oxide film. The specimen looked dark gray after the emissivity measurement.

Figure 8 shows a time variation in the normal spectral emissivity of a tungsten specimen when it was heated in a vacuum at 1000°C and then oxidizing gas was introduced according to the second measurement procedure. The specimen shape was just a plane ribbon without folding because the tungsten was so fragile. The normal spectral emissivity of the tungsten specimen was derived by taking the normal spectral emissivity of the rear surface of the specimen coated with the heat-resisting black paint as 0.85 at the wavelength of 0.9μm. The value of 0.85 was obtained for the heat-resisting black paint from emissivity measurements of cold-rolled steel whose front surface was coated with the same paint. It is seen in Figure 8 that a peek of the spectral emissivity at a wavelength between 0.65 and 0.7 was appears as oxidation progress. The specimen looked vivid purple after the emissivity measurement probably due to the characteristic spectral emissivity.

Figure 9 shows a time variation in the normal spectral emissivity of a Monel specimen when the specimen was preheated in the atmosphere, and then heated in a vacuum above 1100°C according to the third measurement procedure. It is seen that the original emissivity spectrum shows waving due to interference of emitted radiation in the oxide film formed on the metal surface in advance, and that the waving begins to disappear at about 1000°C, and then the emissivity spectrum becomes monotonous at a low level being typical for clean metal surfaces. It can be concluded that the oxide film having formed in advance on the specimen surface disappeared during heating in a vacuum.

4. CONCLUSIONS

All of the normal spectral emissivities and the supplementary information on the specimens having been obtained in this work were stored in the database described. The database and the original text files of the emissivity data are formed on a single CD-ROM with a simple application softwear, and the database can be handled with the application software, Access for Windows95®, or ODBC driver.

It is expected that the normal spectral emissivity database is used for development of multiband emissivity compensation techniques in radiation thermometry and for modeling of thermal radiative properties of oxide films formed on metal surfaces. It is planned to disseminate the normal spectral emissivity database to researchers and engineers interested in this field by copying on a CD-ROM

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REFERENCES

1. Y. S. Touloukian, D. P. DeWitt; *Thermal Radiative Properties, Metallic Elements and Alloys, The TPRC Data Series*, Vol.7 (IFI/Plenum, New York, 1970).
2. M. Kobayashi, M. Otsuki, H. Sakate, F. Sakuma and A. Ono, this volume.

FIGURE CAPTIONS

Fig. 1. Data selection form of the database.

Fig. 2. A displayed graph from the database showing a time variation in the normal spectral emissivity of a nickel specimen at the wavelength of 2μm. The specimen was heated at 1100°C in a vacuum, and then the air was introduced into the vacuum chamber at the flow rate of $10cc{\cdot}min^{-1}$. The average surface roughness of the specimen in the vertical direction was 0.25μm.

Fig. 3. Time variations in the normal spectral emissivity of a nickel specimen and in the effective thickness of the oxide film on the specimen surface. This is from the same data source as Figure 2. (a) for the emissivity at the wavelength of 1.1μm, (b) for the emissivity at 2μm, (c) for the emissivity at 3.7μm, and (d) for the effective thickness of the oxide film.

Fig. 4. Normal spectral emissivities of electromagnetic steel (JIS 50A1000) specimens heated at 1100°C in a vacuum. (a) as-rolled specimen, (b) polished specimen, (c) specimen abraded by an abrasive paper of JIS #1500, (d) specimen abraded by JIS #800, and (e) specimen abraded by JIS #150.

Fig. 5. Time variations in the normal spectral emissivities of four specimens of Inconel 601 at the wavelength of 2μm. The specimens were heated at 1000°C, and then oxidized with different gases introduced at the flow rate of $1cc{\cdot}min^{-1}$; (a) 10% O_2, (b) air, (c) 1% O_2, (d) 100ppm O_2. These O_2 gases were balanced by argon gas.

Fig. 6. Time variation in the normal spectral emissivity of a JIS SUS444 specimen when the air was introduced into the vacuum chamber at the flow rate of $0.2cc{\cdot}min^{-1}$.

Fig. 7. Time variation in the normal spectral emissivity of a cold-rolled steel specimen when the air was introduced into the vacuum chamber at the flow rate of $0.2cc{\cdot}min^{-1}$.

Fig. 8. Time variation in the normal spectral emissivity of a tungsten specimen when the air was introduced into the vacuum chamber at the flow rate of $1cc{\cdot}min^{-1}$ (from 0s to 500s), and then $10cc{\cdot}min^{-1}$ (from 500s to 1000s).

Fig. 9. Time variation in the normal spectral emissivity of a Monel specimen oxidized by heating up to about 1000°C in the atmosphere before the emissivity measurement when the specimen was heated at high temperatures in a vacuum.

Nickel

Ni 99.7%

Data ID	Heat process	Evacuator	Oxidizer gas	Surface treatment
niga100v	Oxidizing	Stopped	Air	As rolled
niga111v	Oxidizing	Stopped	Air	As rolled
[redacted]				
nivx111x	Vacuum	Turbo	–	Oxidized(T=1000C,

Surface treatment before the measurement

As rolled

Introduced gas flow [cc/min] 10

Color before the measurement –

Color after the measurement Yellowish dark gray

Surface roughness [micron]

Ra(vertical)	0.25
Ry(vertical)	1.4
Ra(horizontal)	0.36
Ry(horizontal)	1.4

Close / Next metal

Print | Oxidation

Supplement

–

Table

Time(Temperature) or Wavelength – Emissivity

Graph

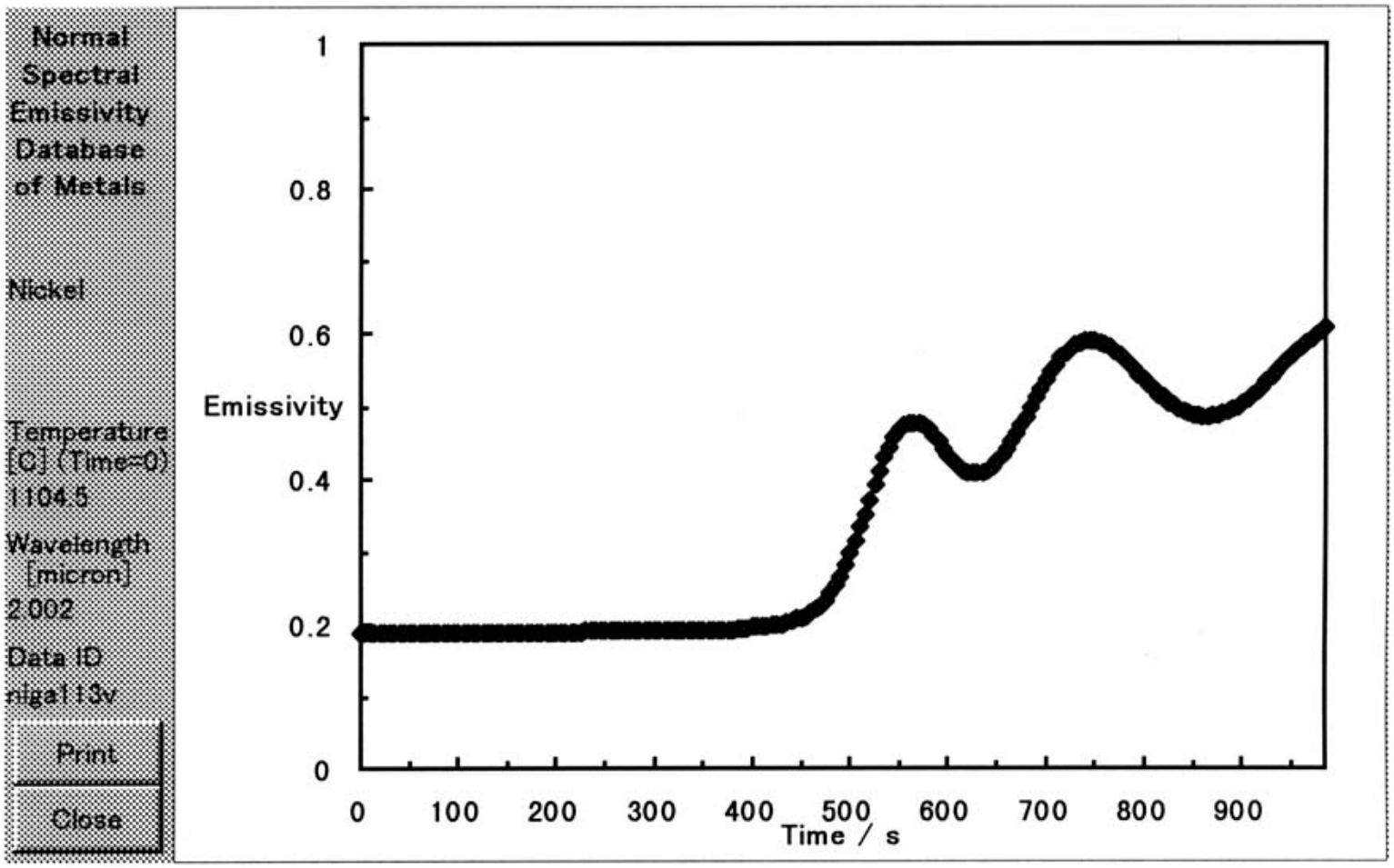
Time – Emissivity

Temperature – Emissivity

Wavelength – Emissivity

Time – Temperature

niga113v Oxidizing Stopped Air


Normal Spectral Emissivity Database of Metals
Nickel
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Wavelength [micron]
2.002
Data ID
niga113v
Print
Close
Emissivity
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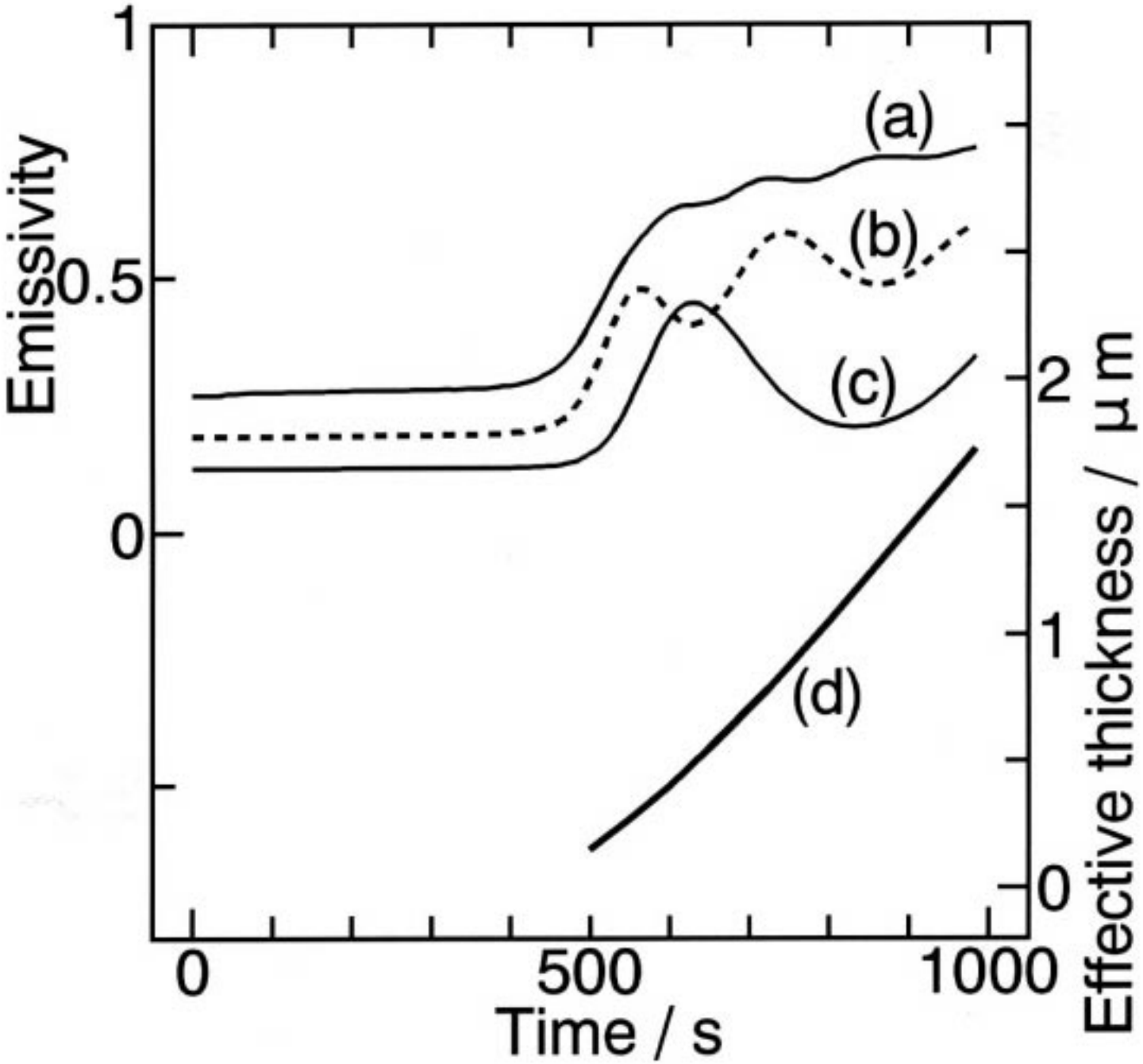
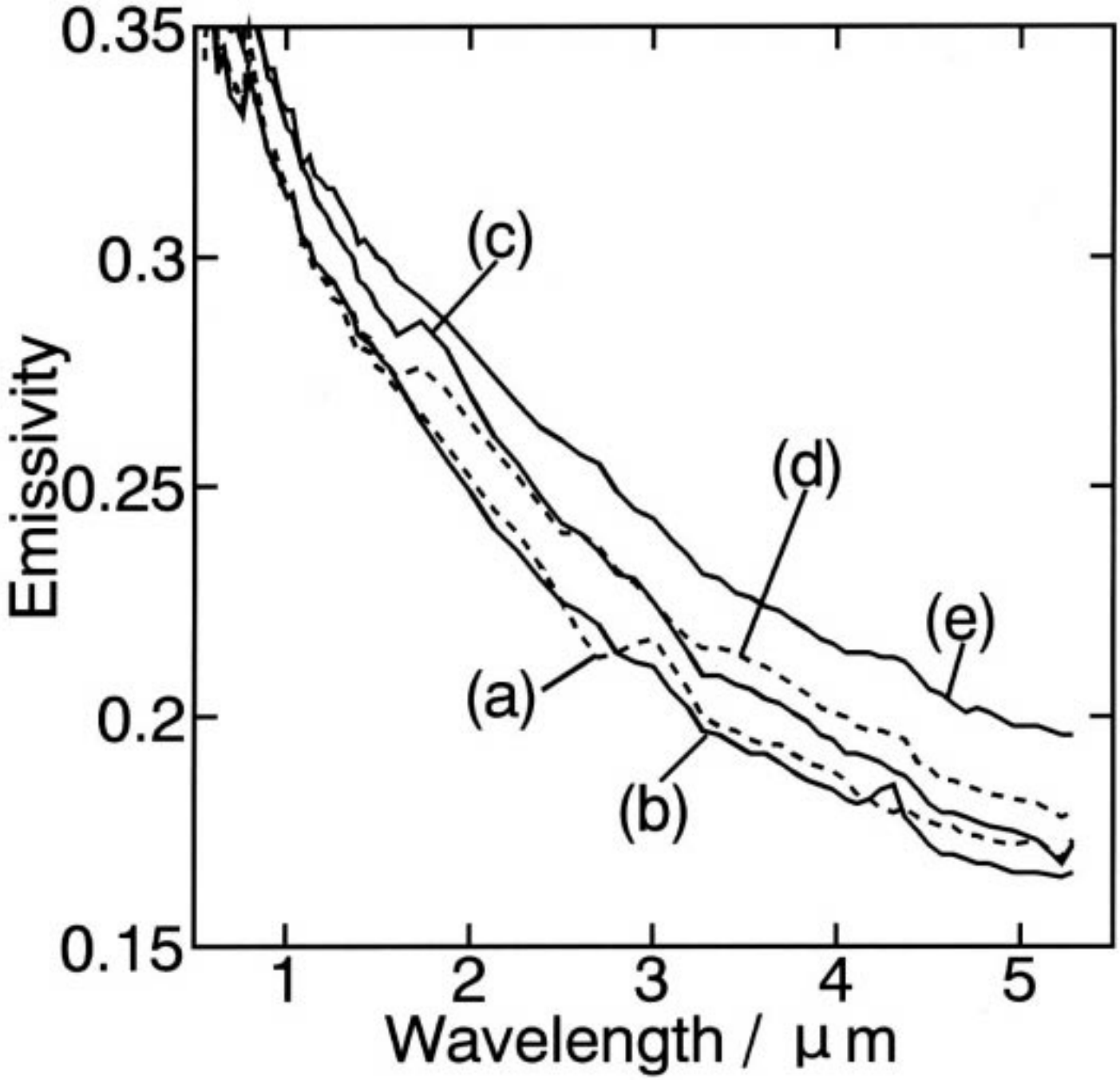
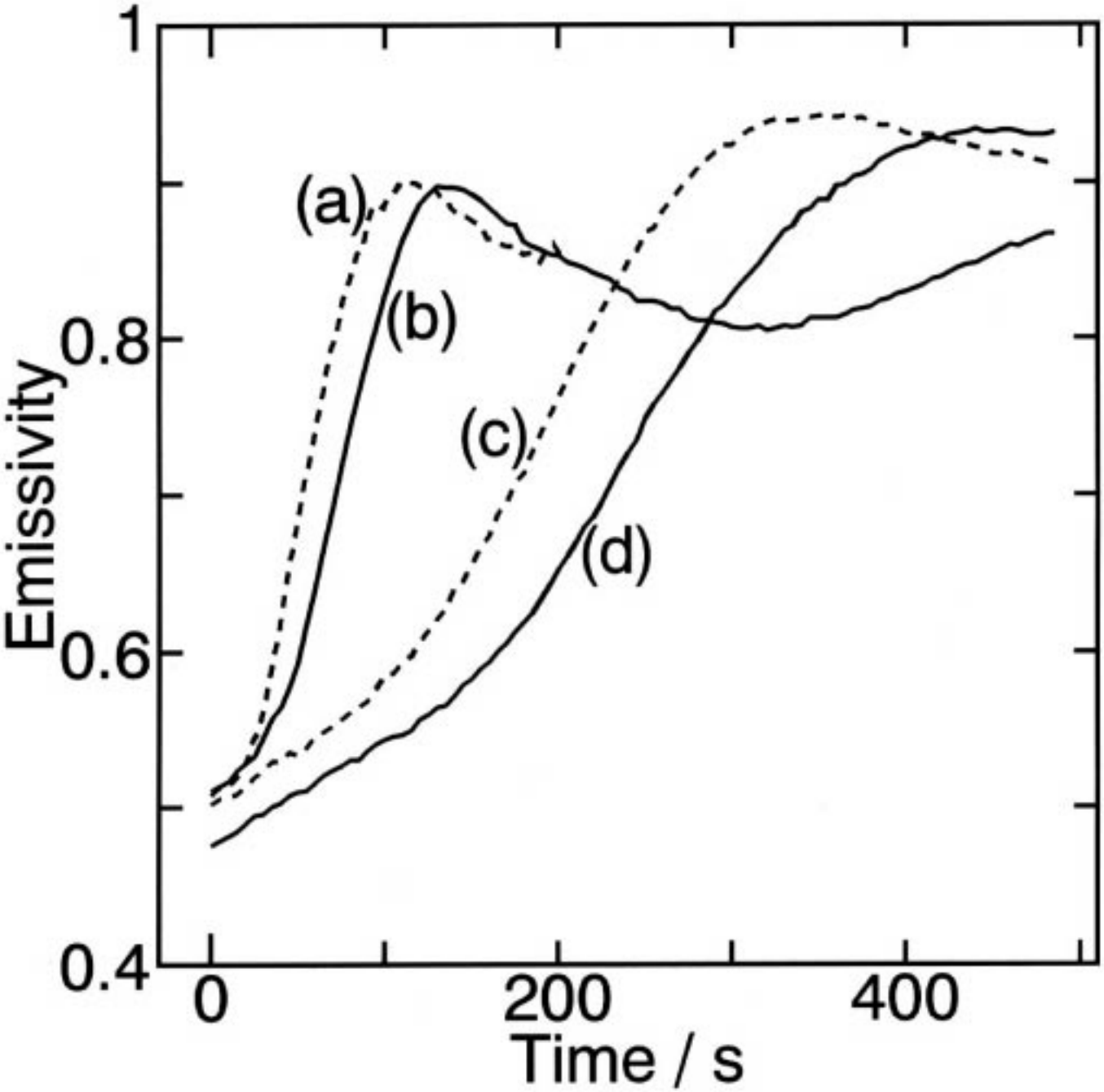
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
700
800
900
Time / s


1
0.5
0
Emissivity
(a)
(b)
(c)
(d)
0
500
1000
Time / s
2
1
0
Effective thickness / μm


0.35
0.3
0.25
0.2
0.15
Emissivity
1
2
3
4
5
Wavelength / μm
(a)
(b)
(c)
(d)
(e)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0.6
0.4
Emissivity
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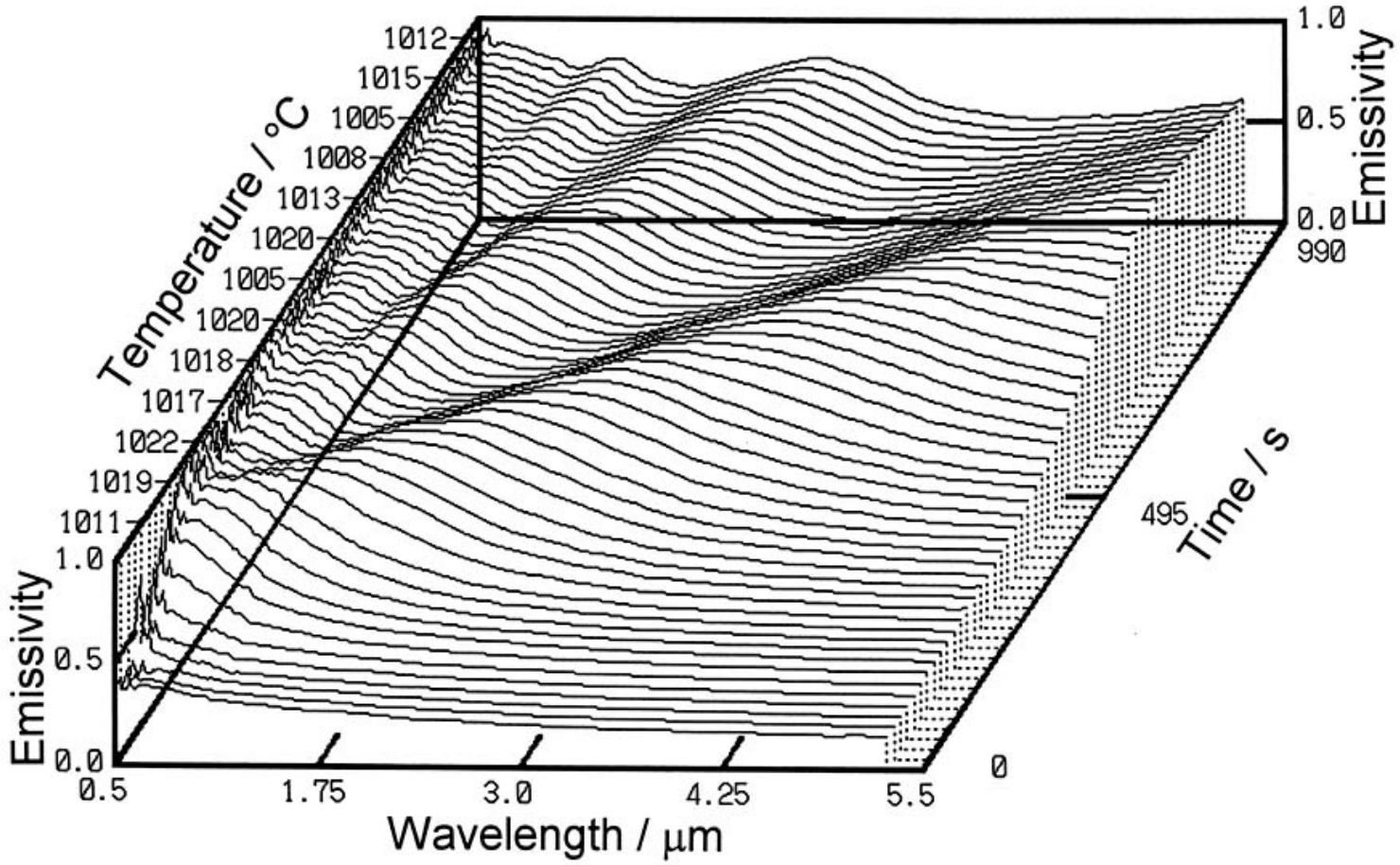
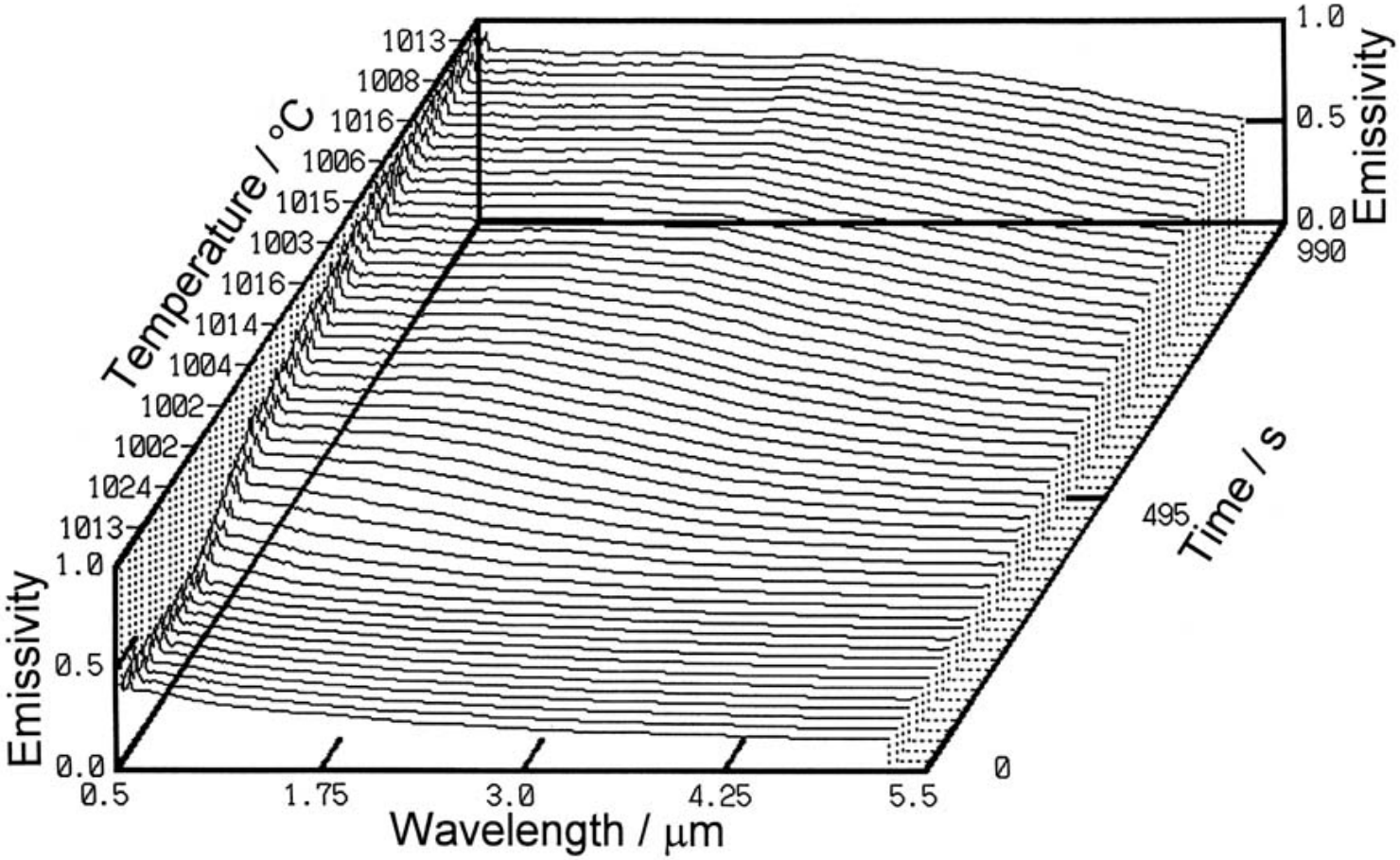
200
400
Time / s
(a)
(b)
(c)
(d)


Temperature / °C
1012
1015
1005
1008
1013
1020
1005
1020
1018
1017
1022
1019
1011
Emissivity
1.0
0.5
0.0
0.5
1.75
3.0
4.25
5.5
Wavelength / µm
0
495
990
Time / s
1.0
0.5
0.0
Emissivity


Temperature / °C
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1008
1016
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1015
1003
1016
1014
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1002
1002
1024
1013
Emissivity
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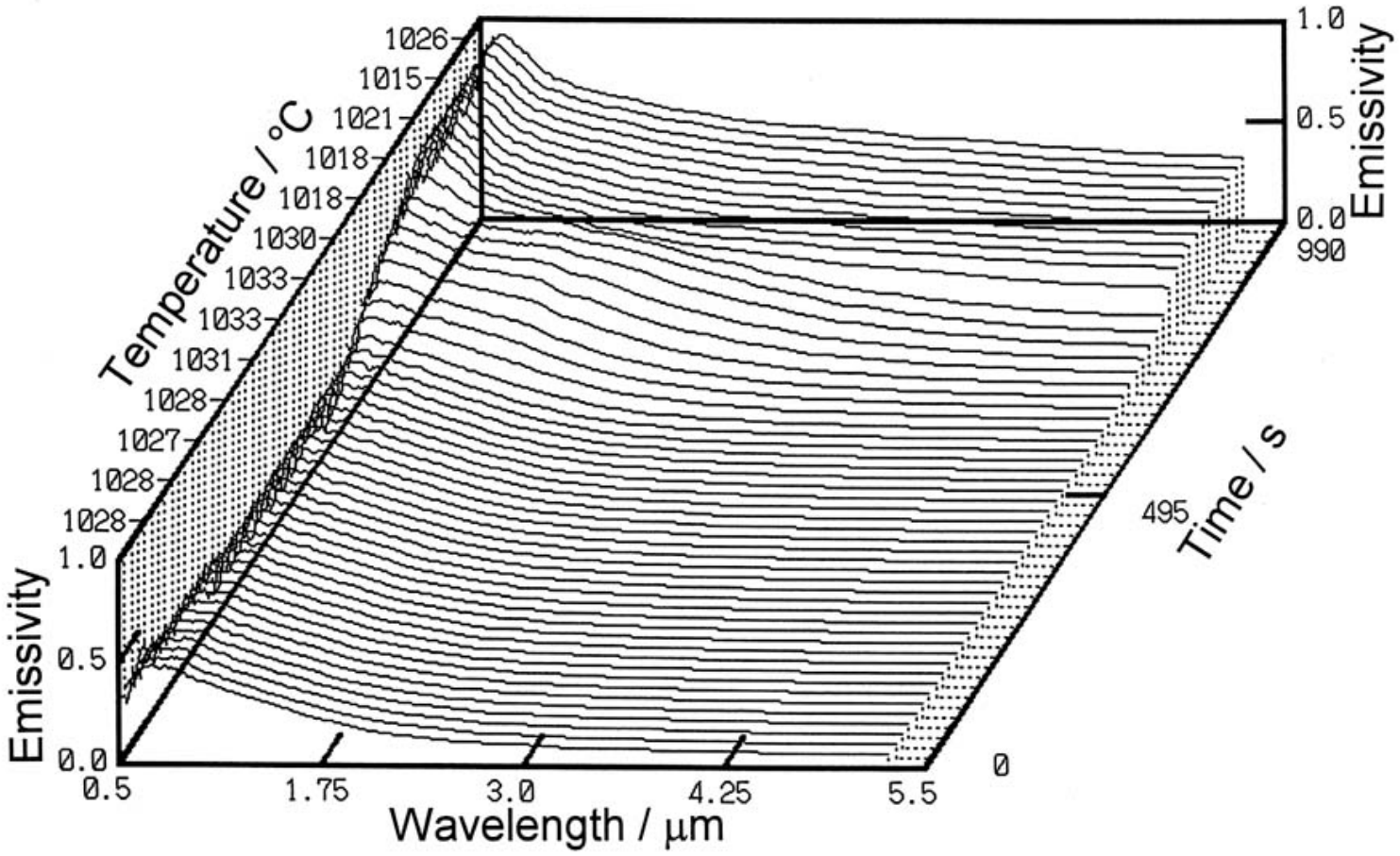
0.5
0.0
0.5
1.75
3.0
4.25
5.5
Wavelength / μm
0
495
990
Time / s
1.0
0.5
0.0
Emissivity


Temperature / °C
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1015
1021
1018
1018
1030
1033
1033
1031
1028
1027
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1028
Emissivity
1.0
0.5
0.0
0.5
1.75
3.0
4.25
5.5
Wavelength / µm
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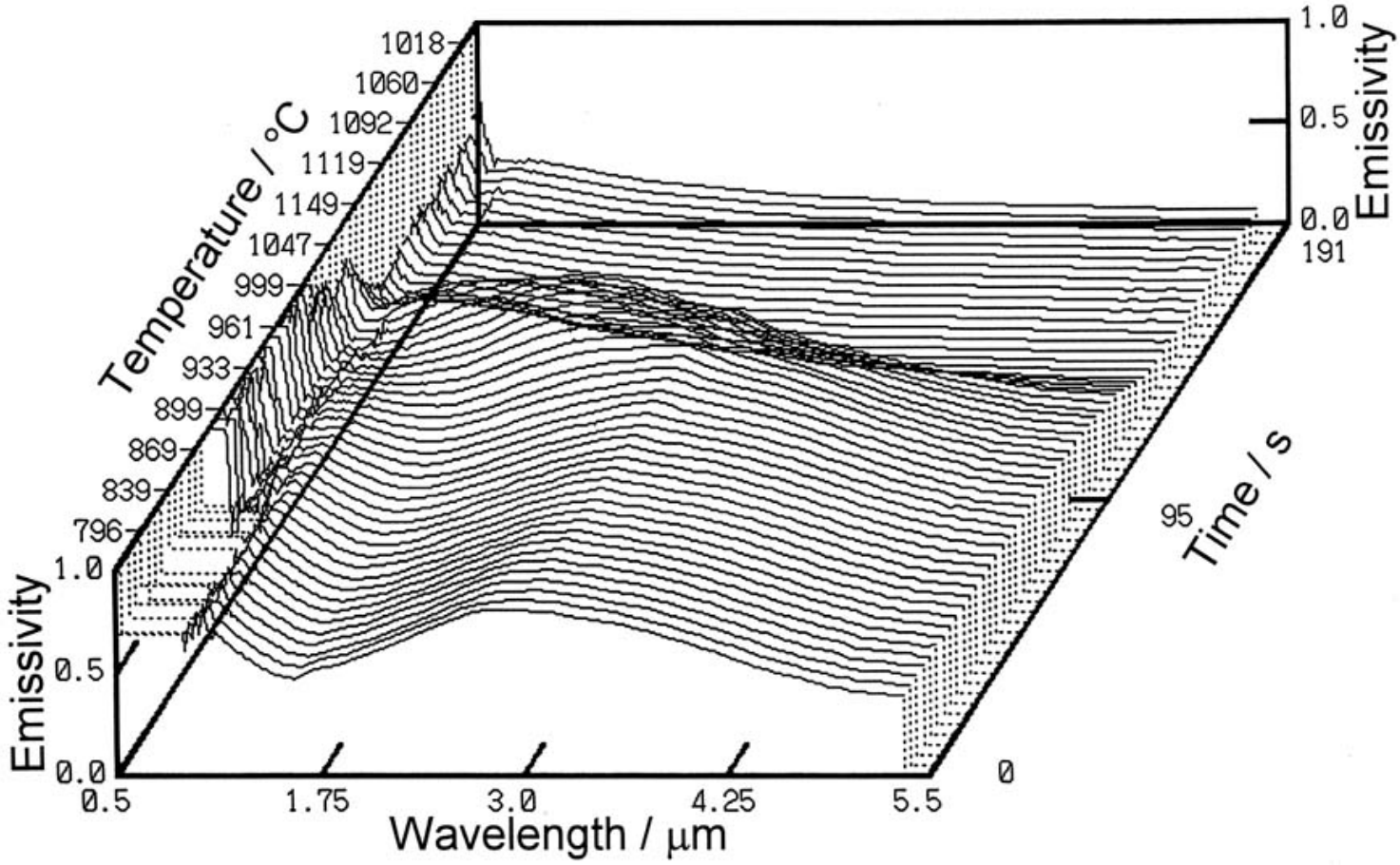
495
990
Time / s
1.0
0.5
0.0
Emissivity


Temperature / °C
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1092
1119
1149
1047
999
961
933
899
869
839
796
Emissivity
1.0
0.5
0.0
0.5
1.75
3.0
4.25
5.5
Wavelength / μm
Time / s
0
95
191
Emissivity
1.0
0.5
0.0