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Spectral Emissivities and Emissivity X-Points of Pure Molybdenum and Tungsten[1]

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Prediction methods for thermophysical properties of metals and alloys such as emissivity are of great interest not only for science but also for the metal working industry as time-consuming and often expensive measurements may not be required. As recent results have shown, an assumed Hagen–Rubens relation for the prediction of emissivity based on electrical resistivity results was not found in the visible spectra. Within this work normal spectral emissivity results obtained with two complete different techniques are presented. On one hand, a multi-wavelength-pyrometry (MWLP) approach has been used to obtain emissivity as a function of temperature at 684.5, 902, and 1570 nm, and on the other hand, a radiance-comparison method was used to obtain emissivity isotherms as a function of wavelength for a range starting from 1 to 24 μm. From results of the radiance-comparison measurements an intersection of the isotherms, often referred to as the emissivity x-point, was found for both investigated materials, tungsten and molybdenum. According to these results, the x-point wavelengths are given by $\lambda_x = 1.41\,\mu\text{m}$ for tungsten and $\lambda_x = 1.55\,\mu\text{m}$ for molybdenum. Based on these x-points and the MWLP measurements, a new prediction method for the liquid-phase behavior of emissivity is developed and discussed.

KEY WORDS: emissivity x-point; molybdenum; multi-wavelength pyrometry; normal spectral emissivity; radiance comparison; tungsten.

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1. INTRODUCTION

The intersection phenomenon of spectral emissivity isotherms (or as found in older literature, spectral reflectivity isotherms) at a single wavelength λ_x referred to as the x-point or the emissivity x-point is commonly known in metal optics. Although the possible existence of this remarkable occurrence in the near infrared has already been noted by Worthing [1] in 1926, no in-depth investigations have been reported until Price published his data in 1947 [2]. Later on, the x-point has been treated from several different aspects; however, none of them succeeded in providing a satisfactory explanation for this phenomenon. As a result, some interesting but controversial studies have been reported, i.e., Latvey [3] reports departures from a single wavelength of intersection and suspects λ_x to be a function of temperature and the x-point itself to be spread over a wavelength interval.

At the moment, it seems likely that the emissivity x-point can only be explained by means of quantum electrodynamics for solid-state materials. Nevertheless, it is believed that the formation of x-points is related to absorption processes within the bound electron states and not to the electrons involved in the conduction process [4].

The x-point is an inherent material property and can be experimentally observed for several pure metals. Basically, the x-point is of great interest for pyrometry, as it defines a single wavelength at which emissivity assumes a constant value and is independent of temperature. Therefore, one can think of constructing a pyrometer operating at this wavelength and of performing temperature measurements which need not be corrected for changing emissivity.

Over the last century, some efforts have been made in determine emissivity isotherms, and the most established results are those published by DeVos [5] for tungsten in 1954. He found an x-point for tungsten at a wavelength of $\lambda_x = 1.27\,\mu\text{m}$, although Ornstein [6] already published similar data for tungsten in 1936 leading to a x-point wavelength of about $1.63\,\mu\text{m}$. The values of Ref. 5 have been used since to convert from radiance temperatures to blackbody temperatures for tungsten strip lamps and are given by OSRAM as the only external reference on their "certificates of calibration" for tungsten ribbon lamps.

The situation is similar with molybdenum, as some references concerning the x-point can be found in the literature. Hiernaut [7] gives a wavelength of $1.215\,\mu\text{m}$ for the x-point of pure molybdenum whereas Touloukian [8] gives a range of wavelengths (~ 1.2–$1.5\,\mu\text{m}$) for λ_x. As can be seen, both literature values are in agreement with each other and narrow down the possible range for the molybdenum x-point.

With these results for tungsten and molybdenum in mind, new emissivity measurements for those two materials with completely different techniques and scopes have been performed as a collaboration between the subsecond thermophysics group at Graz University of Technology, Austria and "Institut für Angewandte Materialtechnik (IAM)" at Universiät Duisburg-Essen, Germany. In Graz, a multiwavelength-pyrometric technique combined with a photopolarimeter has been used to obtain the normal spectral emissivity at 684.5, 902, and 1570 nm as a function of sample temperature, whereas a FT-IR spectrometer was used at IAM to obtain the normal spectral emittance versus wavelength (in the range from approx. 1 to 24 μm) at different selected temperatures.

2. EXPERIMENTAL SETUP

2.1. Setup at TUG in Graz

2.1.1. μs-Division-Of-Amplitude-Photopolarimeter (μs-DOAP)

The normal spectral emissivity at a wavelength of 684.5 nm is measured directly by using a so-called μs-division-of-amplitude-photopolarimeter. This apparatus uses an ellipsometric measurement approach but without any rotating devices with regard to the time scale of about 50 μs per single experiment used for a typical pulse-heating experiment and is based on Stokes formalism for polarized light.

Technically, an initial polarized laser beam is focused onto the surface of the sample wire and the change in polarization of the reflected beam is optically analyzed. As a result, the normal spectral emissivity at the given laser wavelength is obtained[5] as a function of experimental duration which can further be used to determine the true sample temperature from the radiance temperature. More details concerning the DOAP, the data reduction, and the results can be found, i.e., in Refs. 9 and 10.

The liquid-phase behavior of the normal spectral emissivity has been investigated for a variety of different pure metals and, as a main result, three different trends for ε throughout the stable liquid state have been found [11]. Thus, a shift in temperature and all temperature-dependent thermophysical properties have to be considered if emissivity is assumed to be constant (during the liquid phase) for evaluation.

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[5] Actually, normal spectral emissivity is not directly obtained but the optical constants refractive index n and extinction coefficient k from which emissivity is calculated by using Kirchhoff's law.

2.1.2. Pulse-Heating Setup and Multi-wavelength-Pyrometry

The basic setup used for the multi-wavelength pyrometry is identical with the known pulse-heating apparatus for thermophysical-property measurements in Graz. This pulse-heating apparatus has been extensively described elsewhere [12], wherefore any further description is omitted within this paper.

In principle, a wire sample is clamped between two sets of brass jaws and resistively heated in an inert-gas filled chamber while the surface radiance is recorded with optical pyrometers. By calibrating the pyrometer against a reference blackbody-radiation source, the thermodynamic or true temperature of the sample can be obtained directly from the voltage output of the pyrometer, if the emissivity and its trend throughout the liquid state of the material are known.

This setup was adapted for multi-wavelength measurements by adding an extra window for optical observation to the discharge chamber and by recording the surface radiance versus time signals simultaneously with individual pyrometers operating at different wavelengths.[6] Based on the output voltage of the 650 nm pyrometer and the normal spectral emissivity results obtained by the DOAP (at 684.5 nm), the thermodynamic temperature of the sample as a function of time can be determined. The second calibrated pyrometer (operating either at 902 or 1570 nm) is used to obtain the radiance temperature of the sample at the given wavelength. As a result, the normal spectral emissivity ε_x (x denotes either 902 or 1570 nm) can be calculated by using a modified version of Planck's law of radiation:

$$\varepsilon_x(t) = \frac{\mathrm{e}^{\frac{c_2}{\lambda_{650}\cdot T(t)}} - 1}{\mathrm{e}^{\frac{c_2}{\lambda_x\cdot T_\mathrm{r}(t)}} - 1} \tag{1}$$

where c_2 is the second radiation constant ($c_2 = 1.4388 \times 10^{-2}$ mK [13]), λ_{650} is the wavelength of the first pyrometer (650 nm), λ_x denotes the wavelength of the additional pyrometer, T is the true temperature of the sample, and T_r is the radiance temperature at the wavelength x. The index t denotes time dependence.

A more extensive description of the used formalism and data reduction is given in Ref. 14. For better understanding, a schematic flow chart for these multi-wavelength calculations is shown in Fig. 1.

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[6] This MWLP technique uses simultaneous measurements of surface radiance by two individual pyrometers and is (in our special case) limited to combinations where one of the pyrometers operates at 650 nm. This is crucial for the determination of the true temperature as the DOAP operates close to this wavelength.

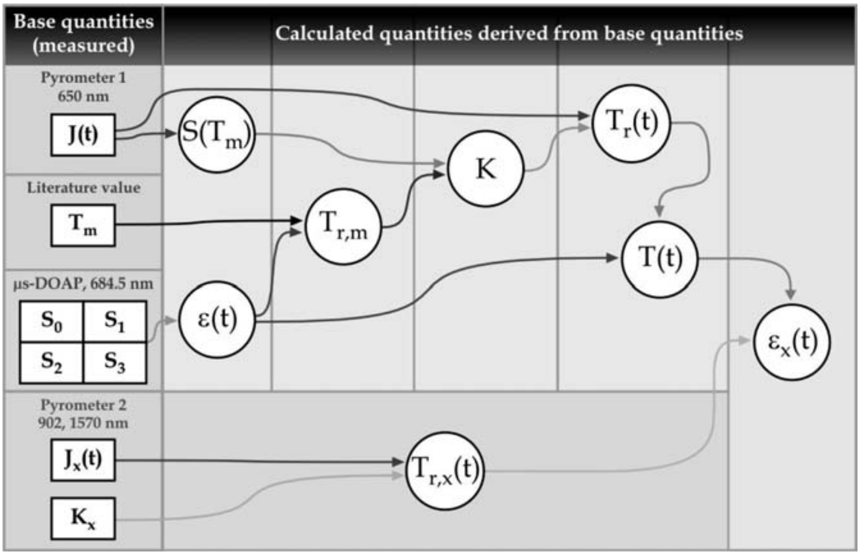

Fig. 1. Flow chart for the multi-wavelength calculations to obtain the normal emissivity at either 902 or 1570 nm versus experimental duration. J, surface radiation; T_m, melting temperature; $S_0 - S_3$, Stokes parameters from ellipsometry; K, calibration factor of pyrometer; S, pyrometer signal; ε, normal spectral emissivity; T_r, radiance temperature; $T_\mathrm{r,m}$, radiance temperature at melting; and T, true temperature. Subscript x denotes either 902 or 1570 nm, depending on the wavelength of the pyrometer used, and t denotes time-dependent properties.

2.2. Setup at IAM in Duisburg

Generally, the apparatus used for measurements of emissivity at IAM in Duisburg utilizes the method of radiation comparison, which means the radiation emitted from the sample surface is compared to the radiation of a blackbody radiator at a certain temperature, wavelength, and under identical optical conditions. A detailed description of the measurement setup can be found in Ref. 15 and schematic diagrams of the setup are given in Refs. 15 and 16. A variety of heat pipes and tubular furnaces are used as blackbody radiation sources to cover a large temperature range. Utilizing these different black body sources a temperature range from 473.15 to 1473.15 K (200 to 1200°C) is accessible. To avoid chemical reactions or oxidization and evaporation of the sample surface during the experiment, different gases (i.e., H_2, CO_2, Ar) can be applied after evacuation of the probe vessel.

The latest addition to the existing setup is a Fourier-transform infrared (FT-IR) spectrometer which replaced the monochromator setup described in Ref. 15. This FT-IR spectrometer allows rapid scans (~several seconds) over the entire wavelength range from 1 to 24 μm, and for the first time, even fast processes like evaporation or temperature-induced surface recrystallizations become traceable. Typical measurement results for normal spectral emissivity versus wavelength and for different temperatures can also be found in Refs. 15 and 16.

It has to be noted that the apparatus at IAM was principally designed for measurements in the temperature range up to several hundred Kelvin. For the measurements reported within this work, only the high-temperature range (1000 K and up) was used.

3. EXPERIMENTAL DATA AND RESULTS

3.1. General Information

All results presented for tungsten and molybdenum in the following section are split into two different groups: multi-wavelength pyrometry measurements (MWLP) conducted at Graz and emissivity versus wavelength results measured at IAM at Duisburg. The former will be referred to as MWLP-results, the latter as IAM results.

The MWLP-measurements for both metals have been performed under a nitrogen gas atmosphere to avoid chemical reactions, whereas for the measurements at IAM, argon was used on molybdenum and pure hydrogen on the tungsten sample. Although different gas atmospheres were used, the results are expected to be intercomparable. The wire-shaped samples for MWLP have been purchased from Goodfellow Cambridge Ltd. (nominal diameter of $\varnothing = 0.5$ mm, purity of 99.95% for both materials) and treated with acetone to remove possible contaminations and grease layers from the surface before the experiment. Both samples for measurements at IAM have been provided by Fa. Plansee, Reutte, Austria and have also been treated with acetone prior to measurements. For all evaluations, where necessary, the following melting temperatures [17] have been used: 3687 K for tungsten and 2895 K for molybdenum.

3.2. Experimental Data

3.2.1. Tungsten

The results from the MWLP measurements with tungsten at different wavelengths (684.5, 902, and 1570 nm) can be seen in Fig. 2. Linear least-squares fits are applied to the emissivity for each wavelength in the liquid state. For ease of reading, the melting temperature of tungsten is indicated in the figure by a vertical dashed line. At melting, the normal

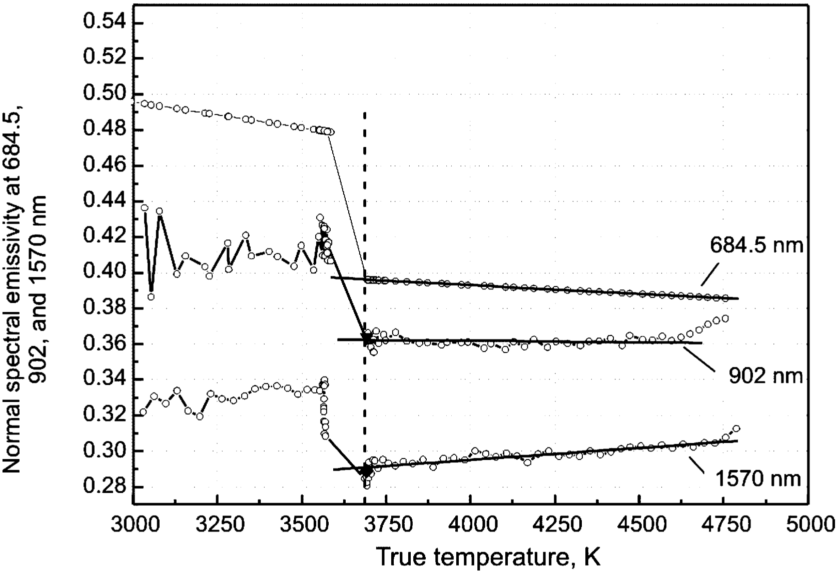

Fig. 2. Normal spectral emissivity of tungsten at 684.5, 902, and 1570 nm as a function of true temperature obtained by means of multi-wavelength-pyrometry. Vertical dashed line: melting temperature (3687 K); solid lines: linear least-squares fits to the liquid states; and solid down triangle\solid diamond: reference values at 906\1500 nm taken from Ref. 18.

spectral emissivity of tungsten takes the values presented in Table I. Furthermore, the trend of emissivity (obtained from the slope of the linear least-squares fit) in the liquid phase at each wavelength is also listed in Table I.

The normal spectral emissivity as a function of wavelength at three different temperatures (973, 1073, and 1283 K) for tungsten obtained with the IAM apparatus in Duisburg is shown in Fig. 3. From the intersections of the three emissivity isotherms (marked by a circle), a x-point at about $\lambda_x = 1.41\,\mu\text{m}$ is found as indicated in Fig. 3b by a vertical dashed line. The actual emissivity value at λ_x is $\varepsilon = 0.380$.

3.2.2. Molydenum

The MWLP-results for molybdenum at different wavelengths (684.5, 902, and 1570 nm) are presented in Fig. 4 with linear least-squares fits added to emissivity for each wavelength in the liquid state. For ease of reading, the melting temperature of molybdenum is indicated by the vertical dashed line. Both the emissivity values at each wavelength and the

Table I. Normal Spectral Emissivity values at Melting Obtained by MWLP for 684.5, 902, and 1570 nm as well as Trends for the Liquid-Phase Behavior of Emissivity at each Wavelength for Tungsten and Molybdenum

Material	$\varepsilon_{684.5}(T_m)$	Trend^a	$\varepsilon_{902}(T_m)$	Trend^a	$\varepsilon_{1570}(T_m)$	Trend^a	$\lambda_x(\mu m)$
Tungsten	0.396	↘	0.363	↘	0.286	↗	1.41
Molybdenum	0.332	↗	0.333	↗	0.284	↗	1.55

Behavior of emissivity throughout the liquid state (based on the slopes of the linear least-squares fits); $\varepsilon_x(T_m)$: emissivity at melting temperature T_m and at wavelength x given in nm; and λ_x: obtained x-point wavelength.
^{a}↗\↘: increasing \ decreasing.

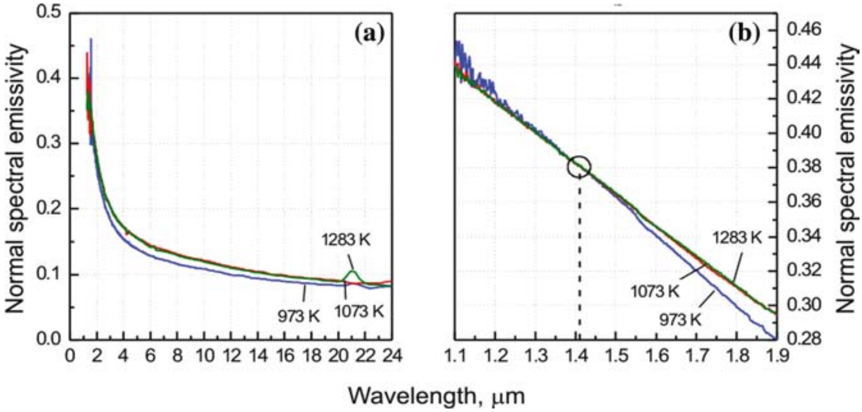

Fig. 3. Normal spectral emissivity for tungsten at 973, 1073, and 1283 K as a function of wavelength. (a) Total range of measurements. Note: features in the emissivity isotherms at about 21 µm are not actual signals, but artifacts from the band absorptions of the air in the FT-IR and the inert-gas atmosphere in the vessel. (b) Close-up of the range with the estimated x-point (circled). Vertical dashed line: estimated wavelength of $\lambda_x = 1.41 \mu m$.

liquid-phase trend of emissivity (based on slopes of fits) are given in Table I.

The normal spectral emissivity as a function of wavelength at three different temperatures (1073, 1273, and 1473 K) for molybdenum obtained with the apparatus in IAM Duisburg is shown in Fig. 5. From the intersections of the three emissivity isotherms (marked by a circle), an x-point at about $\lambda_x = 1.55 \mu m$ is found as indicated in Fig. 5b by a vertical dashed line. The actual emissivity value at λ_x is $\varepsilon = 0.344$.

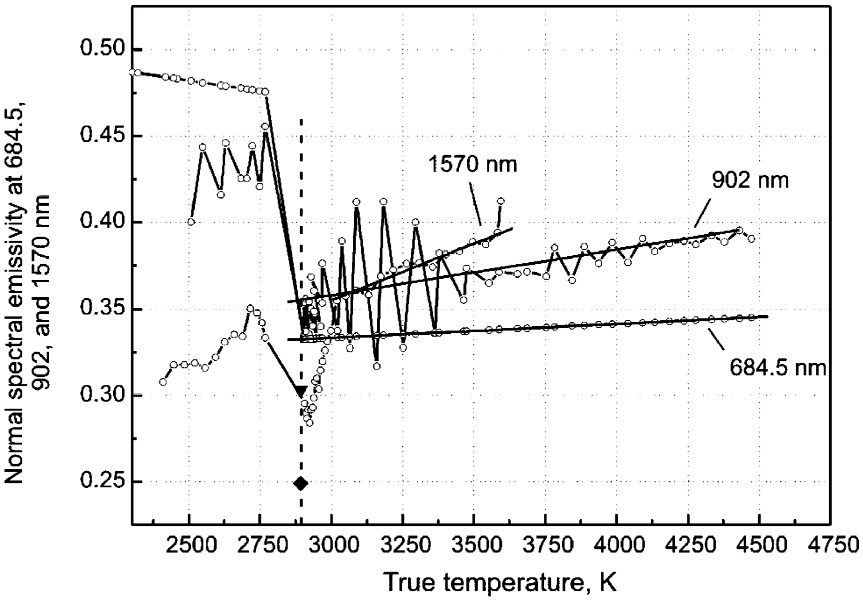

Fig. 4. Normal spectral emissivity of molybdenum at 684.5, 902, and 1570 nm as a function of true temperature obtained by means of multi-wavelength-pyrometry. Vertical dashed line: melting temperature (2895 K); solid lines: linear least-squares fits to the liquid states; and solid down triangle\solid diamond: reference values at 906\ 1500 nm taken from Ref. 19.

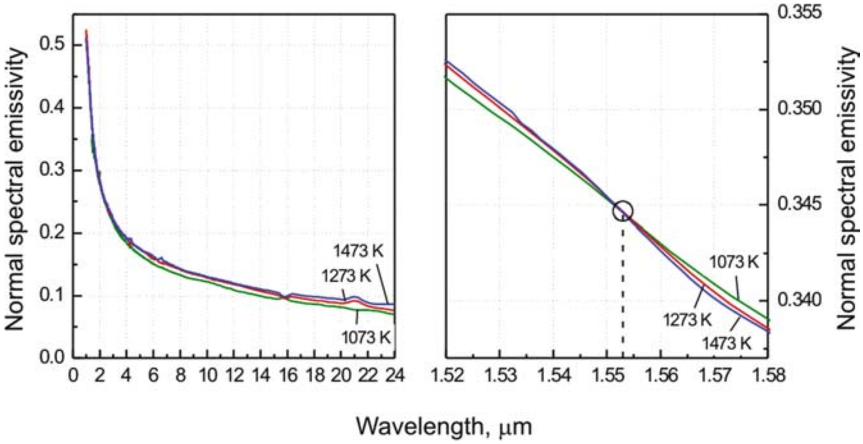

Fig. 5. Normal spectral emissivity for molybdenum at 1073, 1273, and 1473 K as a function of wavelength. (a) Total range of measurements. Note: features in the emissivity isotherms at 4, 6, 16, and 21 μm are not actual signals, but artifacts from the band absorptions of air in the FT-IR and the inert-gas atmosphere in the vessel. (b) Close-up of the range with the estimated x-point (circled). Vertical dashed line: estimated wavelength of $\lambda_x = 1.55 \mu\text{m}$.

4. DISCUSSION

In the following section, the features and specific details concerning each figure will be discussed. As can be seen from Fig. 2 the measured values of emissivity for tungsten at melting agree quite well with literature data. For molybdenum, the agreement between measured data and literature references is not as good.

The emissivity isotherms in Figs. 3 and 5 are not compared to literature values, as such references are scarcely available (nevertheless, values are given in Ref. 8, but are collected from different sources and have not been obtained with identical techniques), and the absolute numbers for emissivity strongly depend on the sample preparation (see, for example, the tungsten values from Ref. 5) as will be further discussed in the following sections.

4.1. Tungsten

It should be noted that the normal spectral emissivity obtained with MWLP at melting shows not only good agreement with data from literature sources but also decreases with increasing wavelength. This behavior for emissivity is nothing new, but has also been found and reported in the literature for most metals and alloys in the solid state and at the melting transition, see, e.g., Refs. 8, 15, and 20 for further details.

Furthermore, after melting, the normal spectral emissivity of tungsten decreases at 684.5 and 902 nm in the liquid state, whereas it increases for 1570 nm. This fact has been observed for the first time, as no literature references reporting similar behaviors can be found. Such MWLP investigations at these three wavelengths have been performed on five different metals (W, Re, Ta, Mo, Nb) leading to the assumption, that the trend of emissivity in the liquid phase may be only determined by the relative position of the measurement wavelength to the emissivity x-point λ_x and the distribution of the emissivity isotherms [14]. In other words, by looking at the isotherms of tungsten in Ref. 5, it can be seen that emissivity at wavelengths longer[7] than λ_x increases as temperature increases and decreases for all available wavelengths shorter than the x-point wavelength. It can be seen from the MWLP measurements that an inflection point of the emissivity behavior has to exist somewhere in the wavelength range $902\,\text{nm} < \lambda < 1570$ nm. This inflection point is assumed to coincide with the emissivity x-point. If this asssumption proves to be applicable, a knowledge of the emissivity x-point and the distribution of the isotherms around the

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[7] According to Ref. 5, this is $\lambda > 1.27$ μm for the special case of tungsten.

x-point could be used to predict the liquid phase behavior (increasing, constant, decreasing as reported in Ref. 11) for each material. To demonstrate this assumption, measurements at IAM have been performed with the goal to possibly detect such intersections of the emissivity isotherms for tungsten and molybdenum.

Results for emissivity versus wavelength are presented in Fig. 3 and show intersections of the three isotherms at about 1.41 μm. This wavelength does not exactly coincide with any given literature references but is in the same range of wavelengths, as DeVos [5] obtains $\lambda_x = 1.27\,\mu\text{m}$, Ornstein [6] obtains $\lambda_x = 1.63\,\mu\text{m}$, Hiernaut et al. [7] obtain $\lambda_x = 1.32\,\mu\text{m}$, and Ref. 8 gives a range from 1.2 to 1.4 μm. With the exception of the value from Ref. 6, all other references are located in the wavelength range of interest where the inflection point is assumed to be from the MWLP results, which seems to support the assumption.

It should be noted that the absolute wavelength for the x-point at IAM may well vary within a certain range, as the difference especially for the isotherms at 1073 and 1283 K is small which makes it difficult to determine exactly the intersection wavelength. Furthermore, a value of $\varepsilon = 0.38$ was found at λ_x which is not in agreement with the values $(\varepsilon(\lambda_x \sim 0.326)$ presented in Ref. 5. This fact seems to stem from a common problem in emissivity measurements; i.e., the sample preparation and heat treatment. Emissivity itself is strongly dependent on the actual surface, the crystalline structure, and the composition (purity, etc.) of the material under investigation as can be seen, e.g., in Ref. 8 for various materials. As a consequence, different values for emissivity are obtained for different materials and the authors also suspect the x-point to slightly change with a variation in the structure or the material composition. DeVos [5] annealed his tungsten strips for 100 h at 2400 K in a hydrogen atmosphere to obtain a stable structure and surface before he conducted his measurements.

Unfortunately, it was not possible to apply such a pre-treatment to the sample prior to measurements at IAM, as the apparatus is not designed for such high temperatures, and the actual composition of the tungsten sample was also unknown[8] . A combination of these two facts could be an explanation for the variation in the absolute emissivity values.

4.2. Molybdenum

The MWLP results for molybdenum differ from those obtained for tungsten not only because the absolute numbers vary, but also the general

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[8] The sample was only specified by the supplier as "high-purity" tungsten.

results are different. Interestingly, the emissivity results do not decrease with increasing wavelength, but for 684.5 and 902 nm the values at melting are almost identical, and throughout the liquid phase ε at 902 nm is higher than the emissivity at 684.5 nm. In the temperature range from 2900 to 3500 K the signal at 902 nm is superimposed by an oscillation. The source of this phenomenon is unknown, but is possibly an artifact from the evaluation routine. However, the result for 1570 nm is even more unexpected as the emissivity at melting is significantly lower than those at 684.5 and 902 nm, but directly after melting ε increases strongly, bends at about 3050 K, and is followed by another increase but this time with a less steep slope. As an overall result, the emissivities for temperatures over 3050 K are higher than for the other wavelengths.

A comparison of the values obtained at the three wavelengths at melting with the published values of Ref. 19 does not show good agreement. As a consequence, the absolute numbers (except for the ones at 684.5 nm, as they have been directly measured with the DOAP) are not as reliable as the ones obtained for liquid tungsten. Nevertheless, the trends for ε in the liquid state are believed to be correct, and as a result, an increasing trend is obtained for all three wavelengths although the liquid-state behavior at 1570 nm shows two different slopes and needs to be further discussed. Following the assumption made for tungsten, the x-point wavelength can be expected to be either smaller than 684.5 nm or larger than 1570 nm, as there is no change in the trend of ε detected within the range of the three wavelengths.

As can be seen from Fig. 5b, the three isotherms measured at IAM for molybdenum intersect at a wavelength of $\lambda_x = 1.55\,\mu\text{m}$. Literature reference values for the x-point of molybdenum are $\lambda_x = 1.215\,\mu\text{m}$ [7] and the range from 1.3 to 1.6 μm [8]. Once again no direct agreement with a single literature value for λ_x is found, but the value of $\lambda_x = 1.55\,\mu\text{m}$ does not only agree within the scatter of the range found in the literature but could also help to explain the abnormal emissivity trend at 1570 nm as this wavelength is in the immediate vicinity of the observed x-point.

By comparing Figs. 3b and 5b it can be seen that the isotherms for both materials show a different behavior at wavelengths around the x-point. At wavelengths longer than λ_x, the emittance for tungsten increases with an increase in temperature whereas it decreases for molybdenum. The opposite behavior can be found for both materials for wavelengths shorter than λ_x. Moreover, for long wavelengths it can be seen from Fig. 3a and 5a that the isotherms for both materials increase with rising temperature. This leads to the interesting speculation that a second x-point might exist for molybdenum in the range $1.55\,\mu\text{m} < \lambda_x < 4\,\mu\text{m}$, as the isotherms are inverted around the x-point compared to 4 μm (at this wavelength, the split in the isotherms is still clearly detectable from Fig. 5a). Further research is needed to clarify if a possible second x-point exists. As has already been stated for tungsten, the absolute numbers for ε of molybdenum at and around the x-point differ from the ones obtained by MWLP or other techniques which is once again related to the differences in the sample composition, the structure of the material, and the actual surface conditions.

5. ESTIMATION OF UNCERTAINTY

According to the guide for the expression of uncertainty in measurement [21], uncertainties reported here are expanded relative uncertainties with a coverage factor of $k=2$. A more detailed and reliable estimation of uncertainty exists for the measurements performed with the DOAP and MWLP due to a better understanding of the various factors influencing the uncertainty.

An estimation of uncertainty for the normal spectral emissivity by using the DOAP is performed by determining the signal-to-noise ratio of different individual measurements and by analyzing the reproducibility of different measurements. For investigations on liquid tungsten and molybdenum, an uncertainty of ±6% for the normal spectral emissivity is obtained.

For results obtained by MWLP, the uncertainty increase with the temperature must be determined with two pyrometers, and the emissivity is calculated from those temperatures and the directly measured emissivity from the DOAP. Since these different contributions to the uncertainty are independent, the overall uncertainty is calculated from the square-root of the sum of the squares of all independent contributions; this results in a uncertainty of ±8% for the normal spectral emittance. The uncertainty of the emissivity results obtained with the IAM apparatus is completely estimated (based on all known influences and individual contributions) and is given by a maximum value of ±10%, although the actual results are expected to be more accurate.

6. CONCLUSION AND OUTLOOK

Within this work, normal spectral emissivity measurements with two different and completely independent methods on tungsten and molybdenum are presented. The results include normal spectral emissivities at 684.5, 902, and 1570 nm as a function of temperature as well as normal spectral emissivity isotherms versus wavelength in the range from 1 to 24 μm.

Based on the liquid-phase trends for emissivity at different wavelengths, it is presumed that an inflection point for this trend exists and that the wavelength for this point coincides with the emissivity x-point for the given material. To support this theory, the x-point has been determined for tungsten and molybdenum and the direct results obtained are in agreement with this assumption.

Although the results are in agreement with the assumption, further studies and measurements must be conducted to substantiate the theory. Therefore, two different directions should be kept in mind. On one hand, the emissivity isotherms for both materials should be re-measured with tempered samples to check if the x-point shifts with wavelength (as literature values for λ_x vary), and on the other hand, the research has to be extended to more materials to validate or reject the assumption. Since the existence of emissivity x-points is not completely accepted throughout the scientific community, a theoretical model would be needed to unambiguously explain the origin of this effect, which has been observed but is not yet understood.

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