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Thermophysical Properties of Rhenium[1]

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Experimental investigations of the thermophysical properties of rhenium at high temperatures (above 2000 K) are scarce and quite recent. Using an isobaric expansion technique, we performed new measurements up to 7000 K under 0.12 GPa argon pressure and report here enthalpy, density, temperature, and electrical resistivity data for both solid and liquid states. Agreement is good with other pulse heating results obtained on this refractory metal ($T_m = 3453$ K), except in the volume increase at melting.

KEY WORDS: electrical resistivity; enthalpy; isobaric expansion; high temperatures; liquid metal; rhenium; specific heat.

1. INTRODUCTION

Most of the physical studies on refractory metals require unusually high temperatures, and consequently, highly complicated systems have been developed to overcome many problems such as chemical contamination of the specimen through reaction with containers, evaporation, loss of electrical insulation and mechanical strength, etc. Dynamic techniques, covering several time regimes (from millisecond to submicrosecond) [1–10], are well suited for these kind of studies in which the heating rates are in the range 10^4 and $10^9\ \mathrm{K \cdot s^{-1}}$.

While data on both solid and liquid refractory metals such as W, Ta, and Mo are available and reviewed in Ref. 11, physical constants at high temperatures of rhenium ($Z = 75$) are sparse. Nevertheless, measurements on solid rhenium are reported up to 2200 K [12, 13] and on liquid

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rhenium up to 5700 and 7400 K [14, 15]. Rhenium has the second highest melting temperature (3453 K) among the elements.

In this paper, we present an investigation of the thermophysical behavior of rhenium up to 7000 K using an isobaric expansion technique (IEX). We focused our attention on the volume increase at the melting, a physical parameter not so easy to obtain for refractory metals. These data are of importance for liquid surface tension, growth, and nucleation experiments [16].

2. EXPERIMENTAL TECHNIQUE

The isobaric expansion system operating at Bruyères-le-Châtel has been described in detail by Berthault et al. [5] and more recently by Boivineau et al. [17]. A scheme of the device is shown in Fig. 1. One should note that no sound speed measurement has been performed on rhenium in the present study.

Cylindrical wires of rhenium (diameter, 1 mm; length, 30 mm) are loaded in an argon gas vessel ($P = 0.12$ GPa). A capacitor discharge bank (30 kV; 20 kA; pulse length, 100 μs) is used to heat the sample. As the environment is isobaric, the electrical energy input is directly related to the enthalpy. Three heating rates were used. The results did not show any influence of the heating rate within the experimental error.

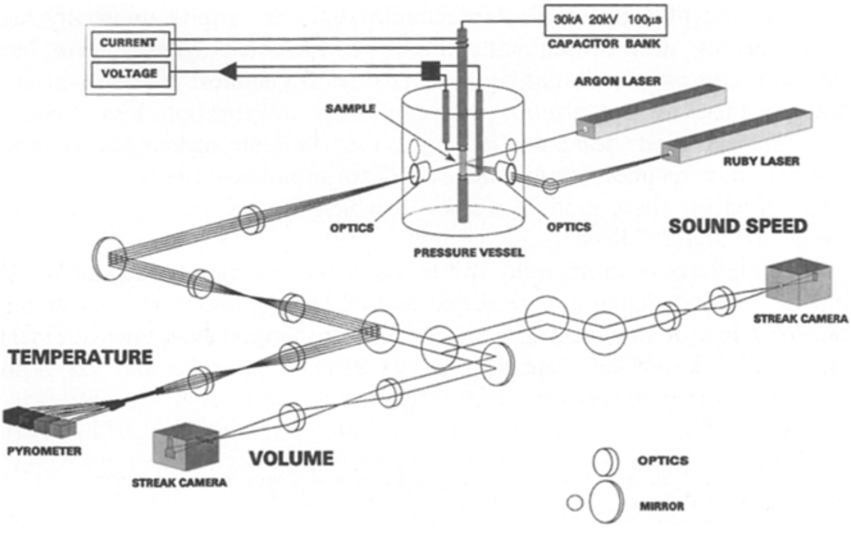

Fig. 1. Schematic drawing of the Bruyères-le-Châtel IEX device.

At any period of time, the following information is available: (a) current intensity through the sample, $I(t)$; (b) voltage drop across the sample, $U(t)$; (c) diameter of the sample, $d(t)$; and (d) thermal emission from the sample surface, $J(t)$.

These measured quantities lead to other thermophysical parameters, namely, temperature $T(t)$, enthalpy $H(t)$, electrical resistivity $\rho_0(t)$, and volume change $V/V_0(t)$. Combining these different terms, one obtains $H(T)$, $\rho_0(T)$, $\rho_0(H)$, $V/V_0(T)$, and C_p. The current, voltage, diameter, resistivity, and enthalpy are measured with an accuracy of ± 0.6, ± 0.6, ± 1, ± 4, and $\pm 1.5\%$, respectively [5, 17].

3. RESULTS AND DISCUSSION

The chemical purity of our samples is given in Table I. The specific volume at 298 K is $4.796 \times 10^{-5}\ \mathrm{m^3 \cdot kg^{-1}}$. The main features of the experiments are gathered in Table II. Selected thermophysical data such as the specific heats at constant pressure for solid and liquid states, C_p^{sol} and C_p^{liq}, the enthalpy of melting, ΔH_{melt}, and the specific volumes at 3453 K, V_{Tm}^{sol} and V_{Tm}^{liq}, are listed in Table III. Rhenium crystallizes in the hexagonal form (space group $P6_3/mmc$). The measured cell parameters are $a = 0.27625(7)$ nm and $c = 0.44623(11)$ nm. Table IV gives the smoothed values for the temperature, T, enthalpy, H, resistivity, ρ, and reduced volume V/V_0 for the 0.12 GPa isobar. Figure 2 shows the enthalpy plotted versus the temperature calculated from the data obtained with the pyrometer at 750 nm. Literature values have been added for comparison purposes. Figure 3 shows the evolution of the reduced volume versus temperature and Fig. 4 illustrates the resistivity with and without expansion correction versus enthalpy.

Enthalpies for solid and liquid rhenium may be represented by (least-squares fit of experimental data)

$$H_s = -0.0779 + 1.797 \times 10^{-4}\, T \quad \text{for} \quad 1817 \leqslant T \leqslant 3453\ \mathrm{K} \qquad (1)$$

$$H_l = -0.0987 + 2.330 \times 10^{-4}\, T \quad \text{for} \quad 3453 \leqslant T \leqslant 6951\ \mathrm{K} \qquad (2)$$

where T is in K and H in $\mathrm{MJ \cdot kg^{-1}}$. These fits lead to a value of C_p of 180 and $233\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$ for the solid and liquid phases, respectively. Although lower values are observed, the agreement with the literature is still good. The measured enthalpy of fusion is $0.158\ \mathrm{MJ \cdot kg^{-1}}$ (Table III).

As mentioned above, only two papers dealt with volume expansion of liquid rhenium [14, 15] and some discrepancy on the volume increase at melting still remains. Our measured volumetric expansion coefficients β are equal to 3.97×10^{-5} and $5.68 \times 10^{-5}\ \mathrm{K^{-1}}$ for the solid and liquid

Table I. Impurities in the Rhenium Samples; Compositions are in ppm by Weight

C	50 ± 5
O	30 ± 10
Fe	25 ± 6
Al	< 10
Ca	< 10
Si	6 ± 2
W	< 4
Mo	2
Pt	< 2
P	1.2 ± 0.6
Ti	< 1
Cu	< 1
Sn	< 1
Zr	< 1
Pb	< 0.6
Cr	0.5 ± 0.2
Ni	< 0.5
Nb	< 0.5
Ag	< 0.5
Sb	< 0.5
Au	< 0.5
Bi	< 0.3
Sr	0.2
Zn	0.2
Ta	< 0.2
Mg	< 0.2
Pd	< 0.2
Co	< 0.2
Mn	< 0.1
Na	< 0.1
K	< 0.1

Table II. Characteristic Features of the Experiments

	Sample No.		
	1	2	3
Argon pressure (GPa)	0.124	0.122	0.122
Voltage of the bank (kV)	16	12	13.4
Maximum current (kA)	18	13	14.5
Heating rate ($K \cdot s^{-1}$)	7.9×10^7	3.7×10^7	4.5×10^7
Maximum temperature (K)	6950	3800	4700

Table III. Selected Thermophysical Data for Rhenium.

	Ref. 18	Ref. 14	Ref. 15	This work
$C_p^{sol}(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$	225		226	180
$C_p^{liq}(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$		250	267	233
$\Delta H_{melt}(\mathrm{MJ \cdot kg^{-1}})$		0.150	0.153	0.158
$V_{T_m}^{sol}(10^{-5}\ \mathrm{m^3 \cdot kg^{-1}})$		5.68	5.31	5.43
$V_{T_m}^{liq}(10^{-5}\ \mathrm{m^3 \cdot kg^{-1}})$		6.52	5.35	5.60

state, respectively. They are consistent with Hixson and Winkler's data (4.95×10^{-5} and $6.64 \times 10^{-5}\ \mathrm{K^{-1}}$) [15]. Nevertheless, at melting, we observed a volume increase of only 3.0%, compared to 14.6% [14] and 0.7% [15]. The larger value was obtained in water at atmospheric pressure, and as discussed in Ref. 10, systematically the volume expansions

Table IV. Measured Thermophysical Properties of Solid and Liquid Rhenium

$T(\mathrm{K})$	$H(\mathrm{MJ \cdot kg^{-1}})$	$\rho(\mu\Omega \cdot \mathrm{cm})$	V/V_0
2500	0.391	110.0	1.095
2600	0.410	111.5	1.099
2700	0.424	112.5	1.102
2800	0.437	112.8	1.106
2900	0.455	113.8	1.110
3000	0.472	115.1	1.112
3100	0.490	116.4	1.116
3200	0.509	117.3	1.121
3300	0.531	118.5	1.125
3400	0.557	118.6	1.129
3453 (S)	0.577	118.0	1.133
3453 (L)	0.735	118.8	1.167
3500	0.752	118.8	1.168
3600	0.782	118.8	1.175
3700	0.801	118.8	1.179
3800	0.826	118.8	1.185
3900	0.849	118.8	1.190
4000	0.868	119.2	1.196
4100	0.890	119.2	1.201
4200	0.917	120.0	1.208
4300	0.943	120.0	1.215
4400	0.968	120.5	1.222
4500	0.996	121.5	1.230

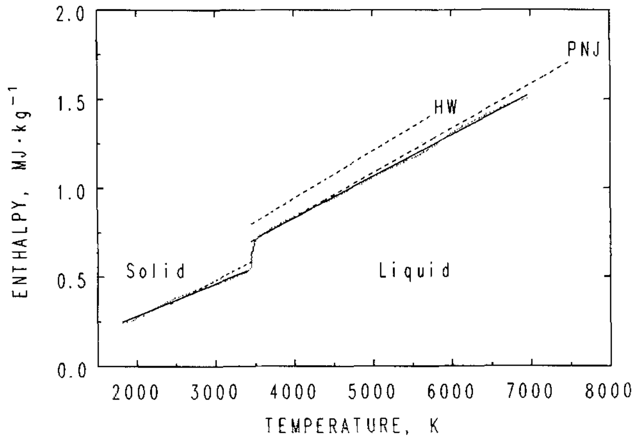

Fig. 2. Enthalpies of solid and liquid rhenium of the present work plotted against temperature (dots). The least-squares fits of experimental data are represented by solid lines. The results of Hixson and Winkler (HW; Ref. 15) and of Pottlacher et al. (PNJ; Ref. 14) are shown as dashed lines.

are higher when operating under these experimental conditions. When using the shadowgraph technique in a compressed ambient medium, the results are more reliable. A volume increase of 3.0% at melting agrees with literature data on other refractory metals. The solid-to-liquid phase transition occurs with a volume increase of 2.9% for niobium [19], 4.2% for

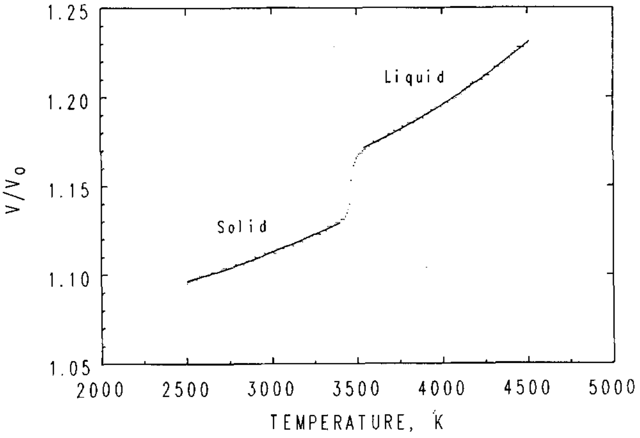

Fig. 3. Reduced volume versus temperature where $V_0 = 4.796 \times 10^{-5}\ \mathrm{m^3 \cdot kg^{-1}}$. The dots and the solid lines represent the experimental data and the least-squares fits, respectively.

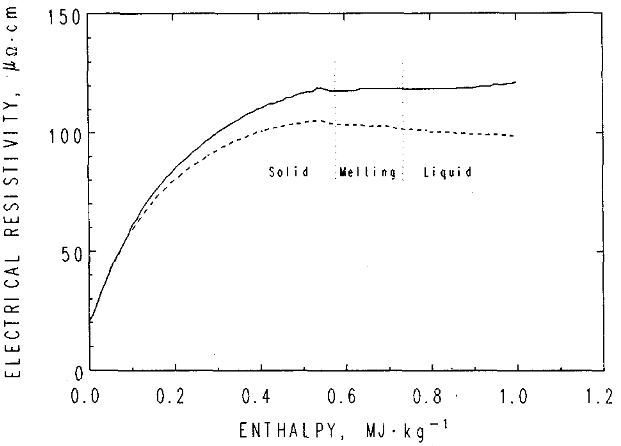

Fig. 4. Electrical resistivity of rhenium versus enthalpy. The solid and dashed lines represent the resistivity with and without thermal expansion correction, respectively.

molybdenum [21], 5.0% for tantalum [5], 6.3% for tungsten [5], 5.0% for iridium [20], and 3.8% for platinum [19].

Surprisingly, the electrical resistivity corrected from the thermal expansion (Fig. 4) does not show a jump at 3453 K. For other metals cited above, the ratio $\rho_{\mathrm{liq}}/\rho_{\mathrm{sol}}$ is close to 1.15 at melting.

4. CONCLUSION

We measured thermophysical properties of rhenium in the solid and liquid phases. Within the experimental uncertainties peculiar to pulse heating techniques, the agreement is reasonably good with literature data, with the largest difference in the volume expansion measurement. On that point, further experiments on well-characterized specimens are needed. Moreover, sound velocity measurements will be performed in the future to complete data concerning the equation-of-state parameters of rhenium.

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