HIGH TEMPERATURE TRANSPORT PROPERTIES OF SOLIDS, VACUUM ZONE REFINING AND RELATED HEAT TRANSFER PROBLEMS

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SUMMARY

The importance of high temperature properties of materials in technology is pointed out in the first chapter. The transport properties of transition metals at high temperatures are interesting from academic point of view also, since spin disorder and s-d scattering provide additional resistance to the passage of electrons in these metals. A brief survey of commonly used methods of measuring the thermal conductivity, electrical resistivity and total and spectral emittances is given and their relative merits and limitations are discussed. There is only one paper (by Donald) devoted to determination of power required to float zone a solid. The results of this work are discussed briefly and it is pointed out that the expression derived by Donald is of little practical value under normal experimental conditions. Needs for analytical solution of the heat transfer problem involved in these experiments as well as for developing new methods for measuring high temperature properties are emphasized. In the next five chapters experimental and theoretical investigations of the high temperature properties of metals and semiconductors are described.

The second chapter is devoted to the description

increases linearly with temperature. The plot for 20% Rh is higher than that for 10% Rh. The two plots converge to each other at 1670^{o}K indicating that Mattheisen's rule is not obeyed by these alloys. The sharp decrease in the electrical resistivity of Zr near 1130^{o}K is due to the phase change from close packed hexagonal structure to the body centred cubic structure. Efforts were made to interpret the observed values of resistivity with the existing theories. Though both Pt and Pd are transition metals, surprisingly, the observed resistivity values are smaller than the values which are calculated from the formula for normal (nonmagnetic) metals. The available theories based on spin disorder scattering or s-d scattering are not suitable to interpret these results.

The observed thermal conductivity K of Pd and Zr as well as of Pt-Rh alloys increases with temperature. Lattice thermal conductivity K_ℓ calculated by using the relation $L = K_e \rho / T$ (where L is the Lorentz ratio, K_e is the electronic thermal conductivity and ρ is the electrical resistivity at temperature T) and $K_\ell = K - K_e$. The lattice thermal conductivity of Pd in the other temperature region and of Zr and Pt-Rh alloys did not obey the theoretically expected T^{-1} law. Lattice thermal conductivity of Pd calculated in this manner is negative in the temperature range 1150^{o}-1250^{o}K. The improvements in the Lorentz relation suggested by earlier workers did not improve significantly the agreement of the observed lattice thermal conductivity with the theory. We badly need a comprehensive theory of metals at high temperature.

Values of spectral emittance ϵ_{λ} of Pd measured in the temperature range 1200^{o}-1400^{o}K at 5 wavelengths in the region 0.52 μm to 0.65 μm are reported. At any wavelength, ϵ_{λ} decreases with temperature monotonically. At any constant temperature, ϵ_{λ} first decreases as the wavelength λ increases, attains a minimum value at 0.58 μm, starts increasing at longer wavelengths and after attaining a maximum at about 0.60 μm, decreases again. Total emissivity of all specimens of Pd studied increases with temperature. However the theoretical relation between ϵ and $\sqrt{\rho T}$ derived by Foote and modified by Parker and Abbott is not obeyed by any of the specimen. The measured values of total emissivity ϵ for oxidized surface of Zr and for Pt-Rh alloys are also reported.

The temperature distribution along a thin rod with its two ends kept at constant high temperatures is of great practical interest. The power required to maintain a float zone in zone refining experiments can be calculated if analytical expression for the distribution of temperature is known. Donald attempted to determine the temperature distribution and the power requirement for a zone purification experiment under the simplifying assumption that the rod is infinitely long and that the temperature and its gradient at the cold end are zero. Since the actual experimental conditions rarely correspond to these boundary conditions, Donald's results are of little practical value.

Since the loss of energy by radiation depends on the 4th power of the absolute temperature at high temperatures, the differential equation describing the heat flow in these experiments is highly nonlinear and complete solution of the equation for the boundary conditions of practical interest cannot be obtained. In Chapter IV, we have solved the differential equation in terms of a convergent power series. We find that in large number of practical cases, first two terms of the series give results within experimental accuracy. Using this series solution, we have derived an expression for the power required to maintain a float zone in the general case for any value of the distance between the float zone and the ends of the rod. Also, based on the series solution, we have developed a new method for determining the conductivity of metals and semiconductors at high temperatures. The method is particularly suitable for materials which cannot be conveniently heated by passing an electric current through it.

The series solution obtained in this work have some limitations. Under certain experimental conditions, the solution does not remain rapidly convergent. If the properties of the material of the rod (thermal conductivity K, electrical resistivity ρ and total emissivity ϵ) are strongly dependent on temperature, the series solution cannot be used conveniently. In Chapter V we have therefore computed the solution of the differential equation, numerically (using computer IBM360), for 102 different cases. The results are plotted in suitable forms so that they can be used to interpret experiments.

In the last chapter (Chapter VI), we compare the results obtained by series solution with those computed numerically. The series solution, wherever sufficiently rapidly convergent, gives results identical with those obtained numerically with the help of the computer. We have performed experiments to check the validity of the series solution, to determine the power required to maintain float zones under different boundary conditions and to demonstrate the suitability of the new method of measuring thermal conductivity. The results of these experiments are also given in Chapter VI.

For a thin rod (5 mm dia) of tungsten with its hot end kept at 1475°K, the first 4 terms of the series solution give result correct within 2% accuracy over a region of 1.7 cm with a total temperature drop of 125°K. The experimental power required to maintain a float zone in silicon rod is 530 watt as compared with the theoretical value 574 watt. The distance of the float zone from the two ends of the rod was 7 and 9 cm the width of the zone was 0.9 cm, and the temperatures of the two ends were 518° and 392°K. The thermal conductivity of tungsten measured by the new method in the temperature range 1220°-1475°K is well within the values reported by earlier workers.

The following papers have been published by the author*.

1. Total and Spectral Emittance of Cobalt, S.C. Jain, T.C. Goel and V. Narayan, Cobalt, No.41,p.191 (1968).

2. Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Method. II. Cobalt, S.C. Jain, V. Narayan and T.C. Goel, Brit. J. Appl. Phys.(J.Phys.D.), 2, 101 (1969).

3. Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Method. III. Platinum, S.C. Jain, T.C. Goel and V. Narayan, Brit. J. Appl. Phys.(J.Phys.D.), 2, 109 (1969).

4. Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Method. IV. Palladium, S.C. Jain, V. Sinha and B.K. Reddy, Brit. J. Appl. Phys.(J.Phys.D.), 2, 1283 (1969).

5. Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Method. V. Zirconium, S.C. Jain, V. Sinha and B.K. Reddy, J. Phys. D: Appl. Phys., 3, 1359 (1970).

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* The maiden name Narayan appears in most of these papers as the papers were communicated before the author was married.

A set of reprints is enclosed at the end of the thesis.

6. Ultrapurification of Refractories, S.C. Jain and V. Narayan, Encyclopaedic Dictionary of Physics, Supplementary Vol. 4; edited by J. Thewlis, (Pergamon Press), 1971, pp. 386-390.

7. Conductivity at High Temperatures, S.C. Jain and V. Narayan, Encyclopaedic Dictionary of Physics, Supplementary Vol. 4; edited by J. Thewlis, (Pergamon Press), 1971, pp. 48-51.

8. Emissivity at High Temperatures, S.C. Jain and V. Narayan, Encyclopaedic Dictionary of Physics, Supplementary Vol. 4; edited by J. Thewlis, (Pergamon Press), 1971, pp. 95-98.

The work which has been done almost independently by the author is included in this thesis. The work reported in papers 1, 2 and 3 is not included in the thesis. The papers 6, 7 and 8 are review papers. The work reported in Chapters IV, V and VI has not yet been published. The following papers are being prepared for publication.

1. A New Method for Determining Thermal Conductivity of Solids at High Temperatures.

2. Power Requirements for Zone Refining Experiments.

3. Numerical and Analytical Solutions of the Boundary Value Problem Determining Temperature Distribution along a Thin Rod Heated at One End to a Constant High Temperature.

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