International Journal of Thermophysics, Vol. 7, No. 4, 1986

Some Research Activities on Thermophysical Properties in China[1]

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Various aspects of the importance of thermophysical property (TPP) studies to science and technology in China are discussed. Several stages of the development of experimental principles and equipment are described. Some examples of TPP applications in economic practice are presented. Theoretical and methodological studies in this field are summarized. The presentations are limited mostly to work on solids.

KEY WORDS: specific heat; thermal conductivity; thermal diffusivity; thermal emissivity; thermophysical properties.

1. INTRODUCTION

It is difficult to make a comprehensive report on all of the research activities on thermophysical properties in China, especially in such a short description. The author gives a brief introduction on some aspects of this subject. There were some national symposia related to the high-temperature and low-temperature thermophysical properties of materials in the early sixties. Unfortunately, those activities were discontinued for several years, until the late seventies. At that time, several societies, such as those of engineering thermophysics, metrology, metals, and solar energy, organized individually some symposia on these topics, the first of which, the National Thermophysical Properties Conference (1st NTPPC), was held in 1984 in Dalian jointly by the three societies engineering thermophysics, metrology, and metals.

[1] Invited paper presented at the Ninth Symposium on Thermophysical Properties, June 24–27, 1985, Boulder, Colorado, U.S.A.

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0195-928X/86/0700-0731$05.00/0

2. THE IMPORTANCE OF THERMOPHYSICAL PROPERTIES (TPP) RESEARCH TO SCIENCE AND TECHNOLOGY IN CHINA

Great attention is paid to thermophysical properties research in China, because of its wide applications in various fields. Some of them are listed below.

2.1. TPP and Thermal Engineering

Thermal engineering is based on thermal design of structures with thermophysical properties as fundamental data. Examples are the design of spacecraft, aircraft, and transportation vehicles and architectural construction [1–3].

2.2. TPP and Thermal Stress Analysis

Thermophysical properties play an important role in thermal stress analysis, especially in the case of structures made of brittle materials under a temperature gradient. Fracture failure can be avoided through correct thermal analysis and by controlling the temperature gradient. The thermal stress analysis of carbon-base nosetips [4] is one of the examples.

2.3. TPP and Material Science

Thermophysical properties are sensitive to microscopic structures of materials. Studies in this field are an important part of material science, espcially for those materials exposed to high temperatures, such as superalloys, refractory metals, ceramics, coatings, pyrolytic graphites, and composite materials. The relationship among processing technique, microstructure, and thermophysical properties is widely studied in China [5–7].

2.4. TPP and the Microscopic Process in the Condensed State of Matter

Thermophysical properties show the collective and statistical behavior of a large number of elementary particles. Some microscopic processes that happen in condensed matter can be studied by the observation and analysis of thermophysical properties. Some theoretical and experimental results in this area have been obtained [8].

2.5. TPP and Nondestructive Testing

The thermovision technique is a very powerful tool in nondestructive testing of materials and structures [9]. These are closely related to the abnormal changes in thermophysical properties around defects.

2.6. TPP and Biological Science

Pathological changes are always accompanied by certain thermophysical changes of the organs and tissues, which can be explored nondestructively by thermovision and temperature measurements. These techniques can be used as powerful tools in medical diagnosis [10].

2.7. TPP and Geological Science

Thermophysical properties research is conducted for both soils and rocks [11, 12]; some of the results have been applied to either agriculture or industry.

2.8. TPP and Metrological Science

The importance of thermophysical properties research to metrological science has been widely recognized [13–16]. This is the case especially for the National Institute of Metrology and for some local institutes of metrology. A standard equipment system is going to be established in both Beijing and Chengdu. A data bank on TPP has been established in Chengdu in recent years.

3. THE DEVELOPMENTS OF EXPERIMENTAL METHODS AND EQUIPMENT

The developments of experimental studies on thermophysical properties can be divided into several stages described as follows.

3.1. The Setup of a Complete System for TPP Determination

It was realized in the early sixties that a complete system for TPP determination was necessary in the early stage of development. Thermal conductivity was measured mostly by steady-state methods [17, 18]. The results are accurate, but the experiments are time-consuming. Specific heat was measured by both calorimetric [19] and differential methods [20]. The measurement of radiative emissivity was accomplished by calorimetric methods [21]. An innovation of thermal expansion determination at high temperatures was the microfurnace and direct observation with the optical comparator [22].

3.2. Multifunctional Equipment and Automation

The second stage of development was to make the equipment multifunctional and automatic.

Thermal conductivity, electric conductivity, total emissivity, and spectral emissivity of graphite at high temperatures can be measured simultaneously on a rod in vacuum by electric heating [23]. Similar equipment was also designed for performing measurements on metals and cermets [24]. Some of the equipment was designed for measurements on both solids and liquids [25–27] or loose materials [28].

The advantage of the unsteady-state (transient) method for measuring thermal diffusivity is widely accepted in China. Several systems employing the pulse technique have been developed in various parts of the country [29–34]. Some new principles were suggested for measuring TPP such as simultaneous measuring of thermal diffusivity, specific heat, and thermal conductivity by the laser pulse heating–cooling method [31]. A combination of a blackbody cavity and laser pulse heating permits a more accurate measurement of specific heat [35]. Some achievements have also been made by the method of information theory [36].

The introduction of computers and microprocessors makes the equipment for measuring TPP more automated and the data treatment more efficient, such as the self-adiabatic drop calorimeter [37, 38], apparatus for measuring radiative properties [39–41] and the guarded hot plate [42–44].

Higher measurement speeds, smaller specimen sizes, multifunctional automated equipment, and computerized data processing systems were the main objectives pursued by the Chinese scientists in the second stage. Most of these objectives were achieved during the past 10 years.

3.3. Standardization and Instrumentation

Parallel with the development of research activities on TPP, standardization of the methods, apparatus, and calibrating specimen is needed. Consequently, several special symposia were held on different subjects such as a direct-heating method for measuring thermal conductivity and electric conductivity [45], the guarded hot plate, and the laser pulse method. Some commercialized instruments for measuring TPP have been on the market for several years. These activities constitute the third stage.

3.4. Measurement of TPP Under Conditions Simulating Actual Conditions

Since many of the materials, such as composites, or structural components change their structures and properties during utilization or testing, ordinary measurement methods are not satisfactory. This calls for the fourth stage. Some special tests were designed for the determination of the thermal conductivity of materials during ablation [46, 47] and solidification [48]. Some practical instruments were also designed for on-line determination of the surface emissivity of steel plates during production [49] and of some coatings on structural components [50].

3.5. Multidimensional and Nondestructive Determinations

One-dimensional testing is appropriate for isotropic materials and for anisotropic materials only along certain principal axes but generally does not apply for anisotropic materials. The thermovision technique is found to be applicable to temperature field measurements and can be used for thermal conductivity measurements of anisotropic materials [51].

Nondestructive determination of TPP often has advantages over other methods, especially in cases where sample preparation is difficult as it is for rare materials [52, 65]. These requirements promote the developments of the fifth stage.

4. SOME EXAMPLES OF TPP APPLICATIONS IN ECONOMIC DEVELOPMENT

Studies of TPP are widely related to different fields in economic development as follows.

4.1. For Energy Saving

Studies have been made for heat losses, choice of thermal insulating materials, and on-the-spot measurement of thermophysical properties of a network of steam pipelines in a heating system. The results show that the combination of all these studies makes it possible to improve the thermal efficiency of the heating system with significant economic benefits [53–55]. Thermal conductivity is one of the key properties studied [53].

According to the requirements of energy saving, a type of high-emissivity coating for infrared baking have been developed, with total emissivity $\varepsilon \geqslant 0.90$. This coating belongs to the 60 silicon carbide system and can be used for covering the heating elements in industrial drying furnaces at 100–600°C. Industrial practice shows that about 20% of electric energy can be saved in baking of paints, foods, plastics, papers, and cloths. These results were obtained from studies on thermal radiation [56, 57].

The determination of thermophysical properties of coals contributes effectively to the thermal energy engineering field [58].

4.2. For the Iron and Steel Industry

Investigations on thermophysical properties of iron and steel will benefit the iron and steel industry [59–61]. A study on cast iron [59] may be chosen as a representative example. The thermophysical properties of 25 kinds of cast iron (including gray, ductile, vermicular, malleable, alloying, and white irons) have been measured from room temperature to 1000°C, by the laser pulse method and the comparative method. The results have shown that the shape of graphite plays the most important role in the value of thermal conductivity of cast iron. It is found that vermicular iron possesses good thermal shock resistance and preferred characteristics in the other properties concerned. Hence, it is desirable to recommend vermicular iron ingot mold casting immediately with the liquid iron from the blast furnace rather than that melted by the cupola.

In the study of automatic continuous measuring of bath temperature in an oxygen-blowing converter, a correcting formula for the thermal inertia of thermocouple due to slag covering is necessary. After continuous use, the shape of the thermocouple sheath becomes irregular, with complicated, nonuniform, and variable slag covering. The thermophysical properties of the slag covering vary with the temperature. In addition, all the parameters vary with time and differ from heat to heat, and thus it is impossible to derive any correcting formula for the slag-covered sheath. However, this problem can be treated in a different way [60]. Using the principle of similarity, a very simple correcting formula was obtained which permits the determination of the parameters concerned in every heat from the curve representing the temperature decrease obtained after pouring the molten iron into a tapped hot converter. By this formula, the correcting value of temperature can be obtained for every smelting heat.

4.3. For Agriculture

Thermophysical properties studies were substantially concentrated on industrial and laboratory problems during the past decades, but the situation changed somewhat during recent years. Now some of the studies deal with the problems related to agriculture, such as the energy balance in underground storage of fruits. A practical thermal probe for determining thermophysical properties of soils on the ground is shown to be a long cylinder which can be used for the simultaneous determination of thermal conductivity and diffusivity [62]. The hot-wire probe method is demonstrated to be applicable not only to industrial, but also to agricultural problems concerned with the measurement of thermophysical properties of loaded sands [63].

4.4. For Nondestructive Testing

There are the following two aspects in nondestructive measurements: (i) the thermophysical properties can be determined nondestructively without sampling the material; and (ii) the thermophysical properties of the material studied can be used as characteristics indicative of the changes of the structure caused by other factors, e.g., a crack by fatigue or slip by deformation. An investigation of the temperature field of stainless steel during deformation [64] provides a good example of this. A thermovision system has been used to give a dynamical pattern of the temperature field of a stainless-steel plate during tensile deformation. There is an increased amount of infrared emission of energy as the test specimen approaches fracture.

5. SOME ASPECTS OF THEORETICAL AND METHODOLOGICAL STUDIES

Theoretical studies are also active both in macroscopic and in microscopic fields.

5.1. Macroscopic Theory and Mathematical Treatment

A considerable amount of work has been done in this field. Heat conduction problems can be treated with the boundary element method in good agreement with analytical solutions [66]. A theoretical study of the heat and mass transfer in wet porous building material was reported [67]. In this reference, an analytical solution was obtained for transient one-dimensional heat and mass transfer in a semiinfinite porous medium with a constant heat flow at the boundary. A method based on the plane heat source with a constant heat rate in order to determine the moisture transport properties was proposed.

Film boiling in a forced-convective flow along a horizontal flat plate was studied analytically [68].

The data on thermal conductivity measurements of materials during ablation were treated analytically as a moving boundary problem by several methods [69, 70]. The results calculated by these different methods are in good agreement with each other.

The finite-element method is frequently used in solving heat conduction problems; the analysis of the temperature distribution in a freezing wall by the artificially freezing method is an example. This method is generally suitable for the problems of two-dimensional nonlinear heat conduction including latent heat [71].

Various heat transfer studies, both theoretical and experimental, related to different problems are summerized in the literature [72].

5.2. Microscopic Theory and Its Experimental Verification

The microscopic theory of thermophysical properties of solids is one of the topics interesting to Chinese scientists. Understanding the nature of the microscopic processes concerned will contribute to our understanding of the thermophysical properties and will suggest new applications.

The variation of the thermal diffusivity of uniaxially stretched rubber in the direction perpendicular to the stretch was studied both theoretically and experimentally. The dependence of the thermal diffusivity on the extension ratio was derived theoretically according to the model of a rubber molecular network, and a comparison with experimental data was given [73]. The anharmonic vibrations of a one-dimensional lattice has been treated analytically [74]. The thermal expansion coefficient of the lattice and the characteristic time of the thermal expansion process were obtained and physical interpretations were given. The thermal expansion coefficient was found to be in good agreement with the experimental data. However, work to verify the calculated characteristic time is still in progress.

Some theoretical treatments on liquids and radiometric quantities can be found in the literature [75, 76].

5.3. TPP and the Structure of Matter

Some thermophysical properties are sensitive to the structure of matter. A theoretical analysis of the microscopic aspects of high-temperature inorganic composite materials is given in Ref. 77. The heat conduction properties for composite materials were predicted.

Thermal conductivity and diffusivity measurements can be used as a new tool or criterion for materials research. The results on these properties are in good agreement with those obtained from structure analysis, high-temperature strength tests, and phase transitions [78].

Pyrolytic graphite and boron nitride are anisotropic materials, characterized by the large difference in thermal diffusivity in different directions. The studies on these are reported in the literature [79].

5.4. Some Trials in Methodological Studies

Some of the mathematical treatments listed [80–82] can be ascribed to methodological studies, important not only to theoretical, but also to experimental research.

A new approach in applying the computer to the determination of thermophysical properties was developed [80]. The concept is as follows: start with a mathematical model → transform to a set of discrete algebraic equations in temperature with an unknown thermophysical property as the parameter → give a hypothetical value to the unknown quantity → compare the temperature calculated with that of the experiment → if the difference is large, then give another corrected value; if it is small enough, then the value just given is the answer.

An eigenvalue method for the analysis of long-term transient heat conduction is discussed in Ref. 81. It is a rigorous method, based on the conventional variable separation technique together with the finite-element principle. Compared with the common finite-element method, it can be used to obtain results of a higher accuracy and permit a shorter computer time if some restrictions are considered. It was pointed out [82] that the combination of experimental and theoretical methods will provide satisfactory results. With the help of theoretical calculations, the experiments can be simplified; the mathematical derivations can also be simplified by the proper use of physical ideas. For example, theoretical derivation makes it possible to avoid direct measuring of heat in heat capacity determination, such that the influence of the fluctuation of laser pulse energy can be canceled. Using the concept of an equivalent process of heat conduction, the unsteady-state heat flow in a multilayer composite laminate can be solved analytically in simple steps by the homogenization-transformation method. It inspires us to go further into the new approach: the method of physical mathematics.

6. CONCLUDING REMARKS

Most of the work reviewed in this paper is on thermophysical properties of solids. This constitutes only a portion of the studies performed by Chinese scientists in the field of thermophysical properties. A large amount of work on properties of fluids is reported in the Chinese literature, which it was not possible to review in this paper.

ACKNOWLEDGMENT

The author is grateful to Professor Wang Buxuan of Qinghua University for his valuable suggestions and helpful discussions in preparing this paper.

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