frontiers | Frontiers in Thermal Engineering

SPECIALTY GRAND CHALLENGE
published: 26 April 2022
doi: 10.3389/fther.2022.862070

Specialty Grand Challenge for Heat Transfer and Thermal Power

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Keywords: radiative transfer, combined heat transfer, scattering media, thermal radiation, computational modeling

INTRODUCTION

It is known that the study of the processes of heat generation and propagation, as well as its transformation into other types of energy, led to the discovery of fundamental physical laws. We should remember, first of all, the laws of thermal radiation, the discovery of which just over a century ago radically changed physics as a science and became the basis of incredible technical advances. The revolution in theoretical physics has greatly accelerated research in heat transfer and various applications, especially in thermal engineering. Textbooks usually distinguish three ways of heat transfer: conduction, convection, and thermal radiation. However, attempts to solve real problems show that we are usually dealing with combined heat transfer, when different modes of heat transfer interact with each other.

In my opinion, thermal radiation is closer to fundamental science and appears to be a more global phenomenon than other modes of heat transfer. It is not even the fact that life on our planet exists because of thermal radiation from the Sun, and this radiation extends 150 million kilometers to reach the Earth. Contrary to popular belief, thermal radiation turns out to be important at any temperature and at any distance, and its spectrum includes the microwave range used in remote sensing of the ocean surface. This explains why we focus on radiative and combined heat transfer, and the variety of problems involved is so great.

The research topics under consideration are mainly related to various problems of radiation transfer in semitransparent scattering media. Such media are, for example, gases or liquids with suspended particles, as well as various dispersed materials and solids with microcracks or bubbles. Natural objects of study include the Earth's atmosphere and ocean, snow and ice, powders or dust and ordinary sand, and even biological tissues with optically heterogeneous living cells. In thermal engineering these are combustion products containing soot and fly ash particles, porous ceramics and heat-shielding materials, particles in thermochemical reactors and melt droplets from a possible severe nuclear reactor accident. A far from complete set of given examples leaves no doubt about the practical importance of studying radiation propagation in scattering media. Therefore, our editorial team was formed mainly from researchers working in the field of radiative and combined heat transfer in disperse systems.

The classical theory of radiative transfer in such media is based on the integrodifferential equation, which was independently derived early last century by Orest Khvolson and Subrahmanyan Chandrasekhar in connection with the study of radiative transfer in stellar photospheres (Chandrasekhar 1960; Rosenberg 1977). A modern systematic account of the theory of radiative heat transfer can be found in textbooks by Howell et al. (2021) and Modest and Mazumder (2021), and an engineering approach to modeling radiative and combined heat transfer in disperse systems is discussed in Dombrovsky and Baillis (2010).

The radiative transfer equation in a scattering medium does not take into account the wave nature of electromagnetic radiation, which appears most strongly when the radiation is scattered by particles

Edited and reviewed by:
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Received: *25 January 2022*
Accepted: *07 March 2022*
Published: *26 April 2022*

Citation:
Dombrovsky LA (2022) Specialty Grand Challenge for Heat Transfer and Thermal Power.
Front. Therm. Eng. 2:862070.
doi: 10.3389/fther.2022.862070

whose size is of the same order of magnitude as the wavelength of the radiation. However, the wave properties of the medium are taken into account in the coefficients of the equation. In the simplest case of homogeneous spherical particles and with independent scattering (Mishchenko 2018), these properties can be calculated using the rigorous Mie theory. The general solution obtained by Gustav Mie in 1908 and useful approximate theoretical models are described in detail in a well-known monograph (Bohren and Huffman, 1998). At present, similar solutions have also been obtained for optically inhomogeneous particles of complex shape.

Of course, the radiative transfer equation is not always applicable. In some cases, one has to consider alternative physical models up to a very complex numerical solution of the wave equation for the electromagnetic field in an inhomogeneous medium. Also the situation deserves special attention when the so-called near-field radiative transfer takes place and the theory of fluctuational electrodynamics, developed by Sergei Rytov around the beginning of the 1950s, can be used (Song et al., 2015).

It should be said that the numerical solution of the classical radiative transfer equation is by no means a simple task, and in some cases one has to use very complicated algorithms to obtain reliable results (Coelho 2014). Fortunately, in heat transfer problems, as a rule, only such angular-integral characteristics of the radiation field as the radiation flux and its divergence are of interest. This allows (at least at the first stage of the solution) to use simple assumptions for the angular dependence of the radiation intensity and the resulting differential approximations. In addition, in the common case of multiple scattering, the transport approximation for single scattering can be used. As a result, the simple calculation of the differential model can be combined with the usual ray-tracing procedure for the transport radiative transfer equation with a known source function (Dombrovsky and Baillis 2010; Dombrovsky 2019). The limited scope of this article does not allow us to go into detail about the theory and individual methods in radiative transfer. Therefore, below we will only name the main research topics and recommend key publications for each of them on which further work can be based.

We have briefly discussed various approaches to calculating radiation heat transfer. However, the mathematical formulation of the complete heat transfer problem usually involves a transient energy equation with various heat sources and sinks: due to thermal conduction, first-order phase transitions, and convective heat transfer. The integral radiative flux divergence is only one of the terms of the energy equation. Moreover, when convection is taken into account, at least the continuity equation and the equation of motion (usually nonlinear) appear in the equations to be solved. Of course, any detailed analysis of convective heat transfer, especially in turbulent flow, is beyond the scope of the research topics considered. Fortunately, it is possible to use commercial CFD codes for problems with an important role of convection and focus on the radiative heat source. There are also many problems where convection affects the boundary condition only and it is sufficient to analyze coupled radiation and conduction.

The length of this article does not allow us to review the content and objectives of all research topics. Therefore, we will limit ourselves to a few key areas of research, including both traditional and cutting-edge ones.

THERMAL RADIATION IN COMBUSTION SYSTEMS AND FIRE SAFETY

The importance of calculating thermal radiation in combustion systems is obvious and undeniable. The theoretical foundations of this research and some engineering problems have been addressed in a monograph by Raymond Viskanta (2005). Spectral models and the interaction of thermal radiation and turbulence in combustion systems are discussed in more detail in (Modest and Haworth 2021).

It is known that the role of emission, absorption, and scattering of thermal radiation by particles is particularly important in coal or coal dust combustion (Im and Ahluwalia 1993; Krishnamoorthy and Wolf 2015; Wu et al., 2017; Wang L. et al., 2021). In connection with coal combustion, it is worth recalling the concomitant particle pollution in the atmosphere that affects the propagation of solar radiation and infrared radiation from the Earth in the atmosphere. Solving this problem is important for predicting and preventing unwanted climate change.

The problem associated with solid-propellant rocket engines should also be recalled. The fact is that the combustion products of these solid propellants contain micron-sized alumina particles, which determine both the radiative heat transfer in the rocket engine and the visible and infrared emission of the exhaust jet, which is important for missile detection and identification. Information on this topic can be found in monographs (Dombrovsky 1996; Dombrovsky and Baillis 2010) as well as in (Duval et al., 2004; Ponti et al., 2021; Hao et al., 2022). The effect of micron-sized alumina particles in combustion products of solid propellants on radiation of rocket plumes was studied in (Surzhikov 2004; Shuai et al., 2005; Binauld et al., 2019).

In connection with thermal radiation during combustion, the problem of fire safety should be mentioned. First, attention should be paid to the development of relatively simple but reliable methods for calculating radiative transfer, which is usually very time-consuming. When water droplet jets are used to extinguish a fire, the scattering of radiation by the evaporating droplets must be taken into account. This can be done based on the combined two-step procedure proposed in (Dombrovsky et al., 2018). If the task is to shield the thermal radiation of the flame with a water mist curtain, one can refer to a recent study (Dombrovsky et al., 2020). These two articles contain detailed and apparently useful references to publications by other authors. Regarding radiative heat transfer in water mist curtains, one should refer to (Boulet et al., 2006; Collin et al., 2007; Parent et al., 2016).

RADIATIVE HEAT TRANSFER IN ADVANCED THERMAL INSULATIONS

It is known that materials with high porosity and small pore size are preferred for thermal insulation at both high and moderate temperatures. High porosity reduces the contribution of heat conduction in the carrier material, while the small pore size (less than the mean free path of gas molecules) eliminates heat conduction through the gas. As a result, in a good thermal insulation, heat is transferred mainly by thermal radiation, and strong radiation scattering ensures high thermal insulation characteristics of the material. For orientation in theoretical models and basic calculation results for various highly porous materials, it is advisable to consult scientific papers, most of which have been published by Dominique Baillis and her group (Dombrovsky et al., 2007b, 2010; Loretz et al., 2008; Bouquerel et al., 2012; Baillis et al., 2013; Randrianalisoa and Baillis 2014; Coquard et al., 2019). Interestingly, the most important results can be obtained not only by direct numerical simulations using the Monte Carlo method, but also by relatively simple analytical models. Both theoretical modeling and experimental methods should be used in the development of improved thermal insulation. The latter appear to be particularly important.

COMBINED HEAT TRANSFER IN SOLAR ENGINEERING

Various methods have been developed for the direct use of solar energy. The best known are solar cells and industrial cultivation of microalgae. Alongside this, high-temperature thermochemical reactors have been under development for decades, operating on concentrated solar radiation and allowing the production of hydrogen for clean transport and energy, among other things. Studying and modeling combined heat transfer in solar reactors is a major challenge for researchers and involves a number of interesting problems (Romero and Steinfeld 2012; Lipiński et al., 2013, 2021; Wang et al., 2017). This work is far from being completed and is one of the important research topics. Successful work in this direction requires perhaps the deepest knowledge in various areas of heat transfer theory and the ability to identify critical aspects of the problems to be solved.

SOLAR HEATING OF SNOWPACK AND ICE SHEETS

Polar regions of our planet are undergoing rapid changes, including the decrease of ice/snow extent with corresponding impacts on the polar environment (Barry and Hall-McKim 2018). The behavior of massive ice and snowpack under regular summer heating by solar radiation is one of the problems which are not well understood because of interaction of a variety of physical processes. One should recall the interesting finding of the early studies (Brandt and Warren 1993; Liston and Winther 2005) on a deep penetration of shortwave solar radiation in a snowpack. The physical explanation for this effect lies in the interaction of two factors. First, because of the very weak absorption in ice particles, part of the visible solar radiation is absorbed a few centimeters from the surface of the snow cover. Secondly, due to the low thermal conductivity of the snow, a significant part of this heat does not escape to the surface. This heat is transferred by heat conduction to a considerable depth, while the surface is cooled by convective heat transfer and radiative cooling. Unlike snow, the heating of deep layers of thick ice leads to tensile stresses in the surface layer and possible formation of deep and extended cracks.

A recent book chapter (Dombrovsky and Kokhanovsky, 2021) discussed the transport of solar radiation and the associated heat transfer in snow cover as well as in ice cover containing gas bubbles. The developed physical models, analytical solutions, and computational procedures are sufficiently general and can be used in solving various problems related to solar heating of snow and ice. Some of these problems are still waiting to be solved. One of such problems is solar heating of water under a layer of ice, both on the surface of a lake or river and on the surface of the ocean.

NEAR-FIELD RADIATIVE HEAT TRANSFER

We have already mentioned Rytov's theory for near-field radiative transfer. Modern engineering developments in microelectronics and other technologies using complex nanostructured surfaces and very thin gaps have led to a systematic study of this special mode of radiative heat transfer (Zhang 2007; Basu et al., 2009; Song et al., 2015). Undoubtedly, work in this direction is one of the promising research topics for our colleagues. The choice of specific tasks should be based on the literature recommended above.

THERMAL THERAPY OF HUMAN TUMORS

Hyperthermia or thermal therapy is the oldest method of treating superficial human tumors. In modern thermal therapy of superficial tumors infrared laser radiation is often used. In particular, a painless procedure based on asphyxiation of the tumor has been proposed (Dombrovsky et al., 2012). Modeling of thermal processes in this approach is discussed in a just-published article (Dombrovsky 2022). Other hyperthermia methods using a variety of physical effects on tumors are currently under development. This is a great challenge for modeling related physical processes. I would only caution against the side effects associated with blood flow and the human neural network.

RADIATIVE COOLING OF THE EARTH SURFACE

Those of us who live in the mid-latitudes and spend summers in the countryside know that when the sky is clear, mornings are much colder than the evening before. The reason for this is the radiative cooling of the Earth, water, and everything outside the house. The fact is that much of the heat radiation at normal temperatures, according to Wien's displacement law, falls in the 8–13 μm wavelength range (the window of atmospheric transparency). The latter directly contradicts the common misconception that CO_2 is a greenhouse gas.

The radiative cooling effect has attracted increasing attention from researchers (Raman et al., 2014; Hossain and Gu 2016; Leroy et al., 2019; Zhong et al., 2020; Wang T. et al., 2021). Generally, the challenge is to select special coatings to increase the cooling of buildings in hot climates. However, sometimes attempts are made to reduce radiative cooling, which is relevant in cold climates (Dombrovsky et al., 2007a). The study and optimization of cooling is related to the properties of thin films and very fine particles and is actively pursued with the improvement of modern technologies. This defines both the methodology and the objectives of the specific tasks of this topic.

CONCLUDING REMARKS

The section *Heat Transfer and Thermal Power* focuses on radiative and combined heat transfer. A brief overview of our research topics and particular challenges showed the diversity of research problems, including the thermal engineering, geophysics and biomedicine. Universal physical models and mathematical methods make it possible to advance in various directions. The core of our editorial team consists of talented young researchers, and the research topics are very promising. This allows us to believe that our work will be successful and will attract the colleagues from all over the world.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

ACKNOWLEDGMENTS

I would like to thank all my colleagues from universities and research centers around the world for their cooperation, which was important for my experience.

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Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.