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Thermal engineering challenges for the 21st century

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Despite the number of global engineering challenges that have been identified for the 21st century, this article focuses only on those challenges that are primarily germane to thermal engineering. Some specific challenges that have been identified include energy conservation and efficiency of mechanical equipment, energy conservation / thermal management in buildings, development of sustainable energy generation, and advancement of thermal management technologies from nano- to macro-scale. Thermal engineers will also be required to attain a better understanding of fundamental phenomena governing complex and integrated mechanical, chemical and energy systems as well as broaden the perspectives to include an ever-widening range of length and time scales.

Key words: energy, efficiency, thermal management, mechanical equipment, buildings, sustainable, energy generation

INTRODUCTION

In the 20th century engineering recorded some of its grandest accomplishments. During this period (between 1900 and 2000) the world saw for the first time a number of innovations (inventions) that we generally take for granted today. These innovations include automobiles, airplanes, phones, refrigeration, radio and television, rockets, spacecraft, computers, lasers, the internet, and fiber optics. Many others have been compiled in the National Academy of Engineering (NAE's) list of the 20 greatest engineering achievements of the 20th century [1]. In many ways the engineering accomplishments during the century are symbolized by the words "division" and "development". In the early part of the century, engineers divided complex systems into their most fundamental elements for the purpose of study. As the century progressed, scientific understanding enabled the enormous developments of many new technologies.

The topic considered in the article is very broad, and the technical challenges identified are great. It is not possible to include a detailed account of the tasks. Instead, numerous references are cited in the paper in which an interested reader can find in depth discussion of the specific thermal engineering challenges that are identified.

GRAND CHALLENGES FOR THE 21ST CENTURY

As it has already been noted, in the past millennia engineering has recorded some grand accomplishments and has driven advance of civilization. A few years ago (in early 2008) the National Academy of Engineering established an international group of leading technological thinkers and solicited its members and the public at large to identify "the grand challenges for engineering in the 21st century". After receiving the input from a large number of individuals, the Academy announced the 14 most important projects for the future [2]. The NAE Committee's top "Grand Engineering Challenges" were divided into four themes of sustainability, health, reducing vulnerability and the joy of living, included the following: 1) make solar energy economical, 2) provide energy from fusion, 3) provide access to clean water, 4) reverse-engineer the brain, 5) advance personalized learning, 6) develop carbon sequestration methods, …, 13) manage the nitrogen cycle and 14) secure cyberspace. The NAE Committee decided not to rank these challenges, each of which is discussed in a greater detail on the NAE web site [2]. But, from the comments submitted by a large number of individuals it is clear that energy (i. e., conservation, new sources, sustainability, burning of the fossil fuels and capturing as well as storing carbon dioxide, etc.) is at the forefront of the "grand challenges".

It is not surprising that energy is at the forefront of the grand challenges. The global energy consumption (E) is expected to increase according to the simple expression [3],

$$E = N \times GDPC \times GAI \quad \text{(inTW)}, \tag{1}$$

where N is the global population (in billions of people), GDPC is the globally averaged domestic production per capita (in \$/person – year), and GAI is the globally average intensity [in W(\$/year)]. Use of the above equation and the global population estimates yields the following projections of energy consumption summarized in the Table.

The world energy consumption is projected to double from 13.5 TW (terra-watt) in 2001 to 27 TW by 2050 and to triple to 43 TW by 2100. The simple estimate clearly illustrates the challenges the world faces in meeting the global energy demands. Energy and water head the list of humanity's top 10 problems [4] and 21st century innovation topics [5]. Since thermal engineers are associated with different aspects of energy, i. e., generation, use, conservation, etc., the remaining part of this article deals specifically with thermal engineering challenges during the 21st century.

THERMAL CHALLENGES FOR ENGINEERING

It is recognized that the challenges thermal engineers will be facing during this century depend greatly on the particular country, on available energy resources, economy, location on the earth and other circumstances as well as the primary energy use by individuals, commercial, residential, industrial and agricultural sectors. For example, in 2010 in the USA, up to 39% of primary energy was estimated to be used in commercial buildings for heating, cooling, lights, etc., 33% was used by industry and 29% by transportation [6]. These percentages vary greatly from country to country, climate and industrial development. Buildings use about 80% of electricity.

In general, one can imagine a large number of challenges for thermal engineers to include the following: 1) attain a better understanding of fundamental phenomena governing complex and integrated mechanical, chemical and energy systems, 2) broaden perspectives to include every widening range of time scales (from ultra rapid to long term) and length scales (from nanometer to global), 3) increase efforts to integrate thermal engineering with other disciplines, 4) embrace new technological challenges, and 5) collaborate with scientists and engineers from other disciplines to meet these challenges with unique and innovative solutions. Several broad challenges in which thermal engineers could contribute have been identified as follows: 1) advance thermal sciences, 2) promote energy conservation in industrial and manufacturing systems, 3) design energy friendly building systems, 4) take advantage of solar energy, and 5) enable renewable energy utilization. Some more specific challenges for thermal engineering are discussed in the subsections to follow.

Challenges for thermal sciences for next few decades

During the past few decades engineers have addressed thermal management issues ranging in scales from micro to macro. Examples of such devices and / or systems include computer chips, rack-box-board modules, computers and data centers. Enormously great progress has been made by engineers during the past few decades in cooling of electronic components, but major challenges remain [7]. Figure 1 illustrates a schematic diagram of a computer chip package. The thermal management issues are associated with the spreading of heat by conduction, thermal interface resistances (i. e., between chip and substrate and external heat removal from the heat sink) and heat removal. Other probably more familiar devices and / or equipment worth mentioning are microchannels, micro-heat exchangers and large heat exchangers used in power plants and chemical processing industry.

Progress that has been made by thermal engineers / scientists is described in greater detail in some recent accounts [8, 9]. In addition to the well recognized challenges as thermal physics of small scale systems, phase change heat transfer, role of surface on convective heat transfer at phase transitions, effects of coatings on heat transfer and

Table. **Estimates of global energy consumption**

Year	2001	2050	2100
Global population (in billions of people)	6.15	9.4	10.4
Global energy consumption, TW	13.5	27.6	43.0

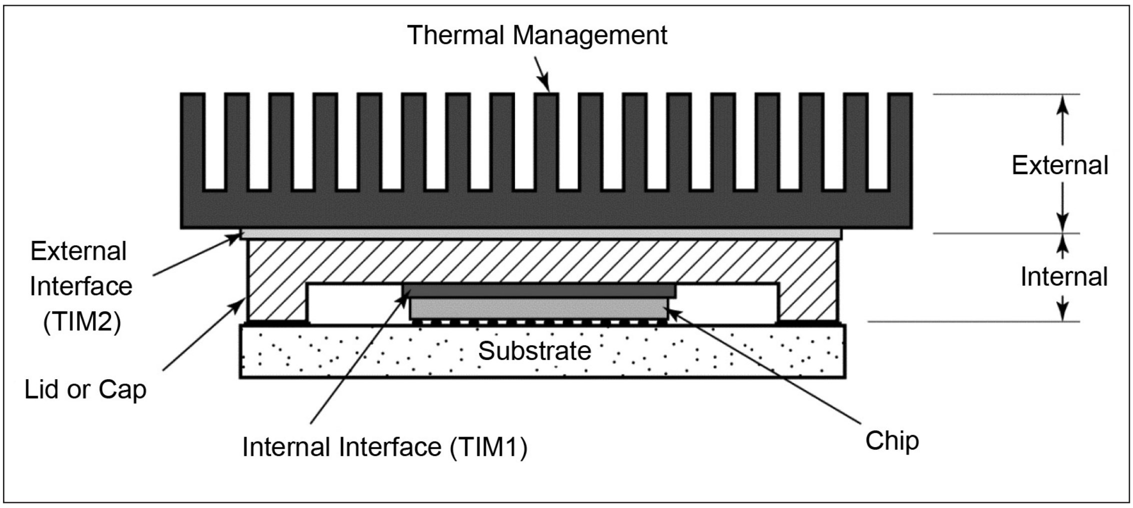

Fig. 1. Schematic diagram of a computer chip package with conduction path to heat sink via TIMs (Thermal Interface Materials). Note that for high-power applications the interface thermal resistance becomes an importance issue

other topics need continued research attention [8, 9]. Some specific challenges on a fundamental scientific level relevant to nanotechnology, information technology are identified below. For example, nanotechnology is considered to be the next industrial revolution and is poised to impact our lives through consumer products, communication, health care, transportation to name just a few aspects. It is generally recognized that interfacial phenomena, size and dimension effects, multi-physics, computational methods and model validation remain important scientific issues. Some specific challenges are identified below.

- Fundamental and applied research in thermal sciences (heat transfer, mass transfer and fluid mechanics) in microscale remains a challenge for the next few decades and includes such phenomena as phase change in microscale channels and devices, measurement techniques, and numerical simulation and modelling.
- Nanoscale heat and mass transport at different interfaces (i. e., solid-fluid, metal-nonmetal and others) is an important scientific and engineering challenge remaining to the explored.
- Heat transfer in small scale, ultrafast heat transfer, nano / microscale thermal radiation, experimental heat transfer on micro- and nanoscale are some additional challenges.
- There is a need for development of predictive multiphysics and computational tools with quantified uncertainties that can address micro- and nano-scale transport in thermal sciences.
- Nano-to- macro integration (i. e., coupling across spatial and temporal scales) remains a challenge to thermal engineers. Theoretical, computational and experimental approaches across scales and disciplines should be embraced during the next few decades.

In the recent past great interest in micro- and nanoscale physics has driven concomitant interest in efficient computational methods to aid in the design and interpretation of experiments, and to understand the behaviour of transport phenomena on micro- and nano-scale. Recent computational CFD (computational fluid dynamics) and CHT (computational heat transfer) in these areas have been reviewed [10, 11], and future challenges identified range from subnano- to- nano- to- micro- to- macroscales. What probably remains as the greatest challenge in the computational area is the notion of "predictive simulation", i. e., computational predictions with uncertainty bounds, an emerging and unexplored opportunity for CFD and CHT [12, 13]. It encompasses areas such as local and global sensitivity analysis, probabilistic simulations which account for uncertainties and eventually melding of the decision theory with simulation and experiments.

Energy conservation and efficiency

Currently energy consumption in economically developed countries is many times greater than in developing countries, which have about 80% of the world population. The global energy demand is expected to increase, and energy conservation and improvement in efficiency are considered to be important means of controlling the demand of energy. Energy conservation and efficiency programs abound around the world. For example, in the United States the Office of Energy Efficiency and Renewable Energy [14] have research and development programs in renewable electricity generation (solar, geothermal, wind and water), energy savings in homes, buildings, advanced manufacturing and sustainable transportation. In the next two paragraphs the focus is only those issues to which thermal engineers are in a special position to contribute their expertise.

Some advanced ideas that that have been identified in the recent past [8, 9] include: examination of novel concepts of conservation and energy efficiency research, exploration of distributed and cascading energy systems, expanded energy harvesting (e. g., heat energy recovery and utilization), development of new generation heat exchangers, recouperators, etc. that use advanced technologies, development of advanced thermal energy storage technologies, promotion of promising industrial / manufacturing opportunities, and exploration of ways to increase efficiency of thermal-power generating plants.

Some more specific examples that can be mentioned involve improving the energy efficiency in industry, including the modification of the chemical distillation processes, exploration of advanced melting, heat recovery and capture of heat from the waste gases in the iron and steel industry, conversion of limestone to lime and others. Developing advanced technologies and making industrial processes more efficient have the potential of reducing primary fossil-fuel energy needs.

Challenges of zero energy buildings

With continued trends for indoor environment there are significant opportunities for thermal engineers not only to improve personalized human comfort in buildings and to reduce energy consumption, but also at the same time to take advantage of the outdoor environment, climate and availability of solar energy. This includes architectural heating and cooling design features of "zero energy homes" and environmentally / energy efficient buildings. Research, development, design and education efforts related to challenges and future directions for energy and buildings ongoing around the world have been recently discussed but challenges remain [15].

In the recent past, there have been and continue to be efforts around the world to promote / advance the NZEB ("Net Zero Energy Building") concept [16]. According to the concept, NZEBs choose a net zero site energy, have a net zero source energy (i. e., produce as much renewable energy as it uses in a year), have net zero energy cost, and produce net zero pollutant emissions. More specifically, NZEBs must reduce energy at a site through energy efficiency and demand-side renewable energy technologies. Among the factors that architects, engineers and owners of NZEBs need to include are daylighting, insulation, passive solar heating, natural ventilation, evaporative cooling, ground-based heat pumps, and high efficiency HVAC (heating, ventilating and air conditioning) equipment. In this regard, thermal engineers have challenges and can contribute in a major way to NZEBs of the future.

Solar–thermal–electric–energy conversion

The conversion of solar radiation into electricity has been dominated by solar thermal power generation and photovoltaic (PV). Photovoltaic cells are deployed widely, mostly as flat panels, whereas solar-thermal electricity generation relies on optical concentrators and mechanical engines (i. e., steam turbine). Here, we focus on the latter method, because it requires important input from thermal engineers, such as storage of thermal energy. In spite of the fact that solar energy is intermittent by nature, solar-thermal power plants that concentrate sunlight on an array of mirrors on a tower are a reality [17]. By integrating heat storage, such power plants can produce electricity day and night. Solar radiation focused by a mirror array is used to heat a liquid (i. e., molten nitrate salt) to more than 400 °C. The liquid is then circulated through a steam generator that powers a turbine to produce electricity. Although somewhat advanced, the present technology has one inherent drawback. At this stage of development, thermal storage plays a key role. For example, a 50 MW(e) solar plant requires some 28,000 tons of salts to store the required heat [17].

Other materials such as ashes from incineration plants, industrial and metallurgical wastes could be used at much higher temperature [18]. Phase change materials (PCMs), which transform from a solid to a liquid state when heated, could be used to an advantage for heat storage because of their high latent heat capacity [19]. Unfortunately, PCMs are not always compatible with the temperatures required for a given application and of their relatively low thermal conductivity for efficient heat transfer. PCM/porous-graphite-matrix composites [20] and supercritical fluids [21] have been proposed as thermal energy storage media and are being investigated. Challenges are ahead in identifying new storage materials. There is a need to broaden the range of accessible temperature and to improve the thermal conductivity for more efficient heat transfer during charging and discharging of the storage unit. In the future, the main challenge will be in storing surplus thermal energy produced during the summer for winter use.

An alternate approach to storing energy (after conversion from solar) is to produce a useful chemical product (i. e., methane). In a solar-thermal conversion process, concentrated solar energy can be used to reach high temperatures and drive strongly endothermic chemical reactions, such as for direct water splitting to produce hydrogen, metal oxide carbothermal reduction, steam methane reforming and others [22]. The efficiency of a solar-thermal chemical reactor is based on the enthalpy change for the process occurring in the receiver and the solar energy input. The combined efficiency of a solar-thermal chemical reactor can be expressed as a product of efficiencies for the solar field-reactor design, absorber and product [22]. In summary, solar-thermal chemical processing has major challenges, but it is also suited for high-temperature chemical reactions where products do not have to be stored as intermediates for downstream continuous processing.

Enabling of renewable energy technologies

The creation of a sustainable energy generation, storage and distribution infrastructure represents a global grand challenge. A major scientific, societal and economic challenge for the 21st century is the changeover from fossil-fuel based energy economy sources to sustainable one. A comprehensive account of the challenge has recently been reported, and a portfolio of solar / thermal / electrochemical energy conversion, storage, and conservation technologies has been discussed [23]. The focus in the discussion is on recent and prospective advances in nanoscale science and technology that offer a high potential in addressing the energy challenge. The interaction of the technologies considered is illustrated schematically in Fig. 2. The recent account [23] not only analyses the physical principles and engineering aspects of these solar energy technologies but also establishes a roadmap for research and development efforts in nanoscale and technologies needed that would advance and accelerate the renewable energy technologies in the near-term (2–5) and long-term (<10) years. Only two of the four conversion technologies that are identified in Fig. 2 are discussed here as they present some challenges to thermal engineers.

In the thermoelectrics (TEs) conversion technology a solar absorber (highly absorbing surface) converts solar radiation into heat and thermally concentrates it onto the thermoelectric elements by means of lateral heat conduction within the highly thermally conductive absorber substrate. The efficiency of the TE power generation can be expressed [24] as

$$\eta = \left(1 - \frac{T_c}{T_h}\right) \frac{\sqrt{1 + ZT - 1}}{\sqrt{1 + ZT + T_C / T_h}}, \qquad (2)$$

where the first factor (in parenthesis) is the Carnot efficiency for any thermal engine operating at a cold-side temperature T_c and a hot-side temperature T_h. The factor ZT is a figure of merit for the thermoelectric material operating between temperatures T_c and T_h [24]. An efficiency of approximately 8.6% can be calculated from Eq. (2) by imposing a temperature difference of 200 °C

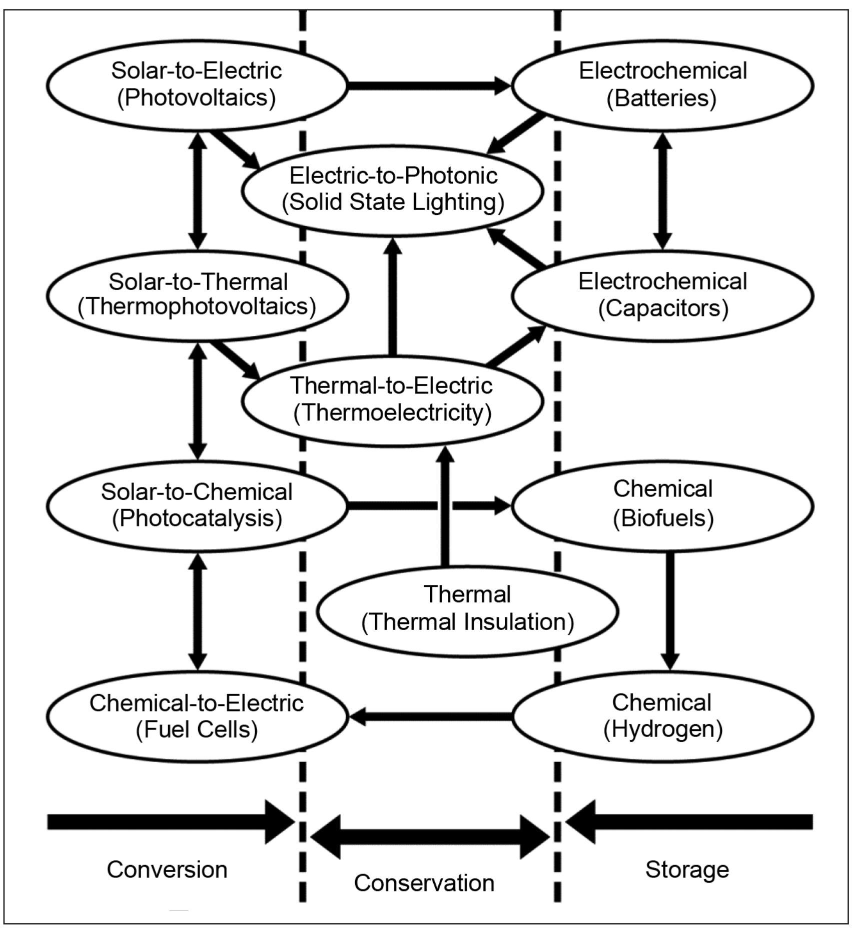

Fig. 2. Portfolio of solar / thermal / electrochemical energy conversion, storage, and conservation technologies and their interactions

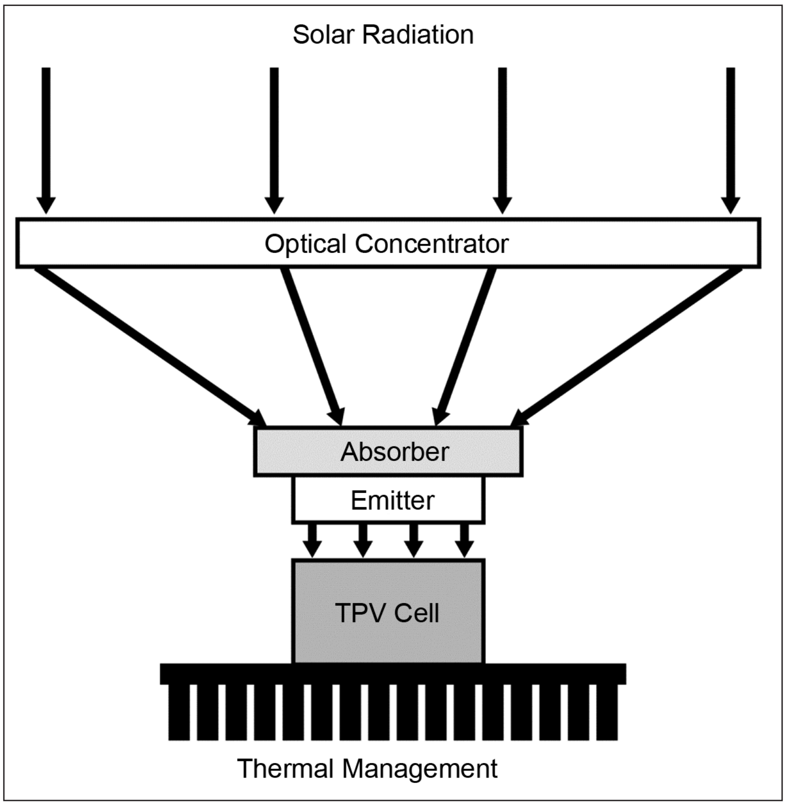

Fig. 3. Schematic illustration of solar thermophotovoltaic (TPV) converter

across an ideal thermoelectric device with $ZT = 1$ and $T_c = 20$ °C. Recently, significant progress has been made in improving thermoelectric materials, but the application of thermoelectrics in large-scale renewable energy conversion has not been demonstrated and remains a challenge [24].

In the thermophotovoltaic (TPV) technology solar energy is first converted to heat and then through a solid-state approach (TPV cell) to electricity (Fig. 3). The theoretical limit of the efficiency of a single TPV converter is 85.4%. Despite their great promise small experimental TPV systems generally exhibit very modest (from 2.4% to 0.8% or less) efficiency [25], mostly due to heat losses such as thermal emission of undesirable mid-wavelength infrared radiation. In TPVs spectral control is a major challenge and different strategies have been pursued in the past. The major difficulty with the approaches lies in the high temperature operation of the emitters, under which the materials lose their stability. The fundamental research challenge appears to be the development of high-efficiency selective surfaces that can operate at high temperatures needed to realize the full potential of the technology [25].

CONCLUDING REMARKS

The humanity is facing significant challenges in meeting the energy needs for the growing population, replacing fossil fuels with renewable energy sources and reducing CO_2 emissions. Global and some more specific challenges on both research and technology levels facing thermal engineers during the next few decades of this century have been identified and briefly discussed in the account.

It is important to note that significant common interests of thermal scientists / engineers working on long term sustainable energy, environment and other global issues (i. e., sustainable water development) intersect and provide motivation for collaborative research with scientists and engineers having different backgrounds.

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21-OJO AMŽIAUS TERMOINŽINERIJOS IŠŠŪKIAI

Santrauka

Nors 21-ojo amžiaus inžinerijai apskritai tenka patirti nemažai globalių iššūkių, tačiau šis straipsnis apžvelgia tik tuos iššūkius, kurie tiesiogiai susiję su termoinžinerija. Straipsnyje gvildenamos problemos, su kuriomis susiduriama termoinžinerijoje, tačiau daugiausia dėmesio skiriama su energetika siejamoms technologijoms. Akcentuojami svarbiausi iššūkiai, apimantys energijos saugojimą ir mechaninių įrenginių energetinio efektyvumo didinimą, energijos taupymą ir šilumos energijos vartojimo valdymą pastatuose, tvarią energijos gamybos plėtrą ir šilumos valdymo technologijų pažangą visoje skalėje nuo nano- iki makro- lygio. Šilumos energetikos inžinieriai ateityje privalės geriau suprasti ir įvertinti fundamentinius reiškinius, darančius įtaką sudėtingoms integruotoms mechaninėms, cheminėms ir energetinėms sistemoms bei išplėsti galimybes atsižvelgiant į vis didėjančius erdvės ir laiko mastelius.

Raktažodžiai: energija, energijos vartojimo efektyvumas, šilumos valdymas, mechaniniai įtaisai, pastatai, tvari plėtra, energijos gamyba

Раймонд Висканта

ВЫЗОВЫ 21-ГО ВЕКА В ТЕПЛОЭНЕРГЕТИКЕ

Резюме

Несмотря на множество глобальных инженерных вызовов в 21-ом веке, в данной статье рассматриваются только непосредственно связанные с теплоэнергетикой, представлены многие и основные вызовы, с которыми постоянно сталкиваются инженеры-теплоэнергетики, но в основном в статье внимание сосредоточено только на энергетические технологии. В некоторые специфические вызовы включаются энерго-хранение, энергетическая эффективность механических устройств, энергосбережение и управление теплоэнергетическими процессами в зданиях, устойчивое и эффективное развитие генерирования энергии, внедрение управления тепловыми технологиями в пределах от нано- до макро- масштаба. Специалистам теплоэнергетики будет необходимо глубже понимать фундаментальные явления и процессы, влияющие на интегральные механические, химические и энергетические системы, а также расширять возможности их применения с учетом постоянно растущих масштабов размеров и времени.

Ключевые слова: энергосбережение, энергоэффективность, управление температурным режимом, механические приборы, здание, устойчивое развитие, производство энергии