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IIR Working Group on
SOLID-STATE COOLING AND HEATING

TERMS OF REFERENCE

INTRODUCTION

In accordance with Article XIX of the International Agreement concerning the IIR and articles 15 to 18 of the Internal Regulations of the Scientific Council of the IIR, the setting up of a **Commission B2** Working Group (WG) is proposed. The following Terms of Reference (ToR) further define the role of the WG.

BACKGROUND

This proposal is especially in line with the UN Sustainable Development Goals which consider Affordable and Clean Energy (7th UN goal), Responsible Consumption and Production (12th UN goal), and the Climate Action (13th UN goal), among the other UN goals, as well as other national and international commitments (e.g. EU Energy Efficiency First Directive, European Green Deal).

According to the IEA, accounting for 50% of global final energy consumption in 2018, heat is the largest energy end-use and contributes to 40% of global carbon dioxide (CO_2) emissions. According to the latest IIR Informatory Note on the Role of refrigeration in the global economy (2019), refrigeration and air conditioning (AC) account for about 20% of global electricity consumption. Demand for cooling and air conditioning is expected to triple over the next 30 years, according to the IEA. Vapour compression can be considered a mature technology with by far the largest market share. The energy efficiency of vapour compression is low for small appliances, requiring significant improvements or the introduction of alternative technologies. Current refrigerants contribute to 7.8% of total global greenhouse gas emissions. Therefore, in parallel with the climate agreements of UN, serious research efforts must be made to decarbonize future refrigerants and improve energy efficiency in cooling and air conditioning.

Industrial process heat accounts for 17% of total energy consumption. Heating of these processes is often done by direct conversion of electricity or gas to heat, which, considering the second law (exergy efficiency), should be prohibited for temperature levels that can be achieved by heat pumps (to date, for temperature levels up to 200°C, at least 30% of industrial process heat can be provided by heat pumps). There is a lack of energy efficient small heat pumps (up to a few kW) capable of producing industrial process heat at high temperatures. In addition, current refrigerants are limited in their temperature range (up to 200°C) for use in high temperature heat pumps. Therefore, significant efforts are needed to develop high-temperature refrigerants and energy-efficient small heat pumps.

One of the important global decarbonization measures also concerns the recovery of the enormous amount of thermal energy contained in waste heat and the use of renewable heat. On the one hand, this can be upgraded with heat pumps. On the other hand, especially in the case of sources with high temperatures, it is easily possible to use them for energy production. The best-established large-scale technology for converting waste heat or renewable heat into electricity (besides steam turbines) is based on the Organic Rankine Cycle (ORC). These devices use refrigerants which also have adverse environmental impacts. For electricity needs in the small kilowatt range, Stirling engines and small ORC are currently being developed and are approaching the application stage. Most of waste heat sources are widely dispersed, have relatively low temperatures (below 100°C), and are best suited for micro-scale use in the milliwatt to few kW range. In addition, they are often available in special environments, such as the exhaust of a car or furnace, electronic devices and systems, photovoltaic thermal or concentrated photovoltaic devices, and others. Existing technologies for using such heat sources are neither cost- nor energy-efficient. In many cases, they cannot be adapted or physically implemented on a small scale.

Energy storage is an important issue for which different strategies and technologies exist. Among these, hydrogen production from renewable electricity and its storage or pumping into power-to-gas networks also plays an important future role. The same holds for biogas or bio-methane, which may lead to future replacements for compressed natural or liquid natural gas. Hydrogen storage can involve storing hydrogen gas, for example, via adsorption or absorption. However, the most mature technology is actually the compression or liquefaction of hydrogen gas. Hydrogen liquefaction can be performed using several cryogenic methods. The energy inefficient conversion from renewables into valuable liquefied biofuels and hydrogen require substantial improvements in energy efficiency. Moreover, small-scale devices may represent an important future market demand, and this domain lacks serious research activities.

The above emphasized issues related to cooling and air-conditioning, heating, energy harvesting, and liquefaction of future fuels call for strong research and development efforts towards more efficient and environmentally friendly technologies and their availability at different scales of use. As a consequence, several alternative technologies have been under development.

Among those, solid-state technologies represent an important domain, which can to a certain, but important extent solve the problem of refrigerants, lead to important reduction of moving parts towards motionless sustainable devices and the circular economy, and last but not least, bring more energy efficient conversion of energy, also for small scale appliances. In general, these technologies concern so called caloric technologies, thermoelectrics, and spin-caloritronics. However, the rapid research activities in the solid-state physics and material science can bring in the near future other alternatives.

For instance, several studies in the last two decades have concluded that caloric refrigeration and heat-pumping technologies, which are still in the research and development phase, are one of the most important alternatives for the future. These solid-state technologies variously utilize magnetocaloric, electrocaloric, and mechanocaloric effects. A material that exhibits more than one of these effects is described as a multicaloric (multiferroic) material with multicaloric effects. The reversibility of the caloric effect, compared with the irreversible compression or expansion of a refrigerant, underscores the promises of caloric technologies. Moreover, as solid refrigerants, caloric materials do not represent an environmental threat. In the recent few years, large research efforts have been also invested into searching the caloric energy harvestings, among which is worth to mention thermomagnetic, pyroelectric, and thermo-mechanical energy conversion, all being able to utilize small scale devices and low enthalpy heat sources. As solid refrigerants, the caloric technologies may undertake the important future part of the liquefaction. Anyway, the magnetocaloric effect was one of important human contributions in the cooling quest for zero Kelvin.

Thermoelectrics (included thermionics) could be perhaps considered as the mature technology, at least for cooling. Despite it is characterized by low second law efficiency (exergy efficiency), it should be mentioned here that the advancements in new materials and nano-technologies can bring motionless and energy efficient cooling (Peltier) devices in the near future. The thermoelectric energy harvesting (Seebeck) is gaining the interest for waste or renewable heat harvesting, and the recent developments related to new materials show good promises that these technologies can overtake other existing solutions. Moreover, thermoelectric heat pumping, especially for high temperature heating, represents one of very interesting and important alternatives. The R&D in thermionics, which enable more efficient operation of the thermoelectric energy conversion will undoubtedly bring important improvements not only for energy harvesting, but may, especially due to the nano-technologies, bring new cooling or heat pump alternatives.

In the last two decades, new solid-state technologies for cooling, heating, and energy harvesting have been investigated. These concern magneto-Peltier, spin-Peltier, spin-dependent Peltier, and anomalous Ettingshausen effect, and may bring future solutions for micro-scale cooling or energy harvesting.

Another important and emerging area of solid-state cooling is optical refrigeration. In the last 25-30 years, the fundamental understanding has been developed with various experimental techniques, advances in materials and device technology. Solid-state laser cooling technologies can be used in infrared sensors and gamma-ray detectors, in optical cavities for metrology, and in cryogenic electron microscopy. The relatively fast cooling with no moving parts makes this technology attractive for other applications as well. Considering the potential scaling, it is therefore possible that these technologies could be extended to other areas of metrology, thermal management and cryogenics.

Although research activities on all the above-mentioned alternatives are intensive, there is still a lack of market available devices. In general, there is a still a lack of intensive applied research and related connection between the solid-state physics, material science, and engineering. In order to bring these technologies to different market niches, and incorporate advancements, the research in these domains needs to be driven by the market and its demand, therefore led by engineers, which are far closer to real market applications and the industry. This of course does not diminish the valuable research efforts in solid-state physics and material science. It simply requires better and much stronger R&D "value chain" between the basic science, applied science and the technology or demand on the market.

OBJECTIVES

The objectives of the Working Group are to foster the international research collaboration of different solid-state cooling, heat pump, and energy harvesting technologies with the aim to provide future energy efficient and environmentally friendly solutions in the variety of different applications. Another objective is to establish the technology transfer by mutual collaboration between research institutes and different industries and to report the progress of developments towards real market applications. The third objective is to broadly promote energy efficient solutions of solid-state cooling, heating and

energy harvesting, which can importantly affect the efficient energy conversion, decarbonization of different sectors, and the circular economy.
Therefore, the specific technical issues to be addressed are:

- The development of new, efficient, cost-effective and environmentally friendly solid-state refrigerants for cooling, heating and energy harvesting,
- Engineering design improvements of energy efficiency, power density, reliability, and other operating features of new solid-state devices,
- Research and development towards specific market applications of solid-state cryocoolers and liquefiers, refrigerators, heat pumps (low to ultra-high temperature), air-conditioners, harvesters of waste or renewable heat, and sensorics,
- Development of solutions that enable cost-effective recycling of different parts or materials of solid-state devices,
- Exploitation of broadest possible number of applications in different economic sectors.

WORKING GROUP WORK PLAN

The working party will perform the following work:

- collecting reliable experimental material,
- listing and studying current scientific and technical problems,
- initiating joint research projects,
- establishing and continuously updating a reference list of research publications on solid-state cooling and heating,
- providing an IIR Informatory Note, accompanied by the Summary for decision-makers (published every two years), which will comprise:
    - critical assessment of different solid-state technologies
    - list of running national and international projects related to topics of solid-state cooling and heating,
    - comprehensive overview in material advancements in properties and processing,
    - comprehensive overview in device features and design advancements, divided into types of technologies and types of applications,
    - market analysis,
    - information on new-coming solid-state technologies.
- organizing workshops and summer schools,
- organizing international conferences every two years with full proceedings,
- creating web page with continuously updated information,
- promoting solid-state cooling, heating and energy harvesting technologies through particular activities, such as promotion at (joint) trade fairs, publications in scientific and non-scientific journals, newspapers, magazines and television,
- providing proactive role of making collaboration and overseas consortiums,
- providing proactive role to promote and support young researchers and women, and internationalization,
- providing proactive role for getting involvement of new-comer industries and research institutes.

IIR COMMISSIONS INVOLVED

Lead Commission: Commission B2 - Refrigerating equipment
Cooperating Commissions: Commission E2 - Heat pumps & energy recovery and Commission A1 - Cryophysics and Cryoengineering

MEMBERSHIP

WG members are expected to be either Commission members, private members or representatives of corporate members of the IIR with a technical expertise enabling them to contribute to the work of the WG.

WORKING GROUP LEADERSHIP

Chair: Prof. Dr. Andrej Kitanovski (University of Ljubljana, Slovenia)
The Chair of the Working Group will be elected for a period of 4 years. After the mandate, the Chair's position is taken by the Vice-Chair of the WG. After the mandate, the Chair of the WG takes the position in the Scientific Committee.
Vice-Chair: Prof. Dr. Luo Ercang (Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, PR China)
The Vice-Chair of the Working Group will be elected for a period of 4 years upon proposal of the WG's Scientific Committee to the IIR.
Secretary: TBD
The Secretary of the Working Group is always appointed by the Chair of the Working Group and for the period of the Chair's mandate.

The Working Group will appoint its officers at its first meeting.

STRUCTURE (optional)

The Working Group will consist of the **Scientific Committee**, which will be formed by scientific/research representatives of the following subgroups, organized in Subgroups:

- Subgroup A: Caloric technologies for heating and cooling
- Subgroup B: Caloric technologies for energy harvesting
- Subgroup C: Thermoelectric technologies for heating and cooling
- Subgroup D: Thermoelectric technologies for energy harvesting
- Subgroup E: Spincaloritronic technologies for cooling, heating, and energy harvesting
- Subgroup F: Solid-State Cryocoolers and Liquefaction
- Subgroup G: Solid-state laser cooling technologies
- Subgroup H: Other solid-state cooling technologies

The **Scientific Committee** will represent a **well-balanced international community of about 30 members**. Members of the Scientific Committee will be selected among well distinguished researchers from all continents: China, Europe, India, South America, USA, Russia, Japan, Africa, Canada, Korea, Turkey, Vietnam, Middle East, Israel, Oceania, and will represent experts from the fields of Mechanical Engineering, Electrical Engineering, Chemistry, Computer Engineering, Material Processing Engineering.

The Working Group will also consist of the **Board of Industries** relevant or interested in the commercialization or exploitation of materials, device parts, devices, and systems related to the solid-state cooling, heating, and energy harvesting.

MEETINGS

The Chair and the Vice-Chair of the Working Group will organize regular online meetings of the Scientific Committee and Board of Industries. The in-person meeting will be held at each international conference. The first online meeting will be held in January 2023. The first in-person meeting will be performed in China, Baotou in August, 2024, when the First Conference of the Working Group will be held and named IIR International Conference on Solid-State Cooling and Heating, *THERMAG10*.

Minutes of the meetings shall be prepared by the Secretary and a copy shall be sent to the IIR head office, to the President of the Science and Technology Council and to the President of Commission B2, E2, and A1. If the meeting is enlarged to a workshop, the organizers will prepare proceedings of the papers presented.

WEBSITE

A website, hosted by the IIR, will be set up in order to disseminate relevant information and to promote the activities of the Working Group and of the IIR. It will be periodically updated under the responsibility of the Chair and Vice-Chair. It will be linked to the Commission B2, E2, and A1, website and to the IIR website.