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State of the art and challenges in measurements and transducers for cryogenic monitoring

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ABSTRACT

Mainstreams in research on measurement systems for cryogenic process monitoring are reviewed with the aim of defining key current trends and possible future evolutions. At this aim, research mainstreams are classified according to the measurand: liquid level, flow rate, and pressure. In these fields, research on innovative measurement systems is surveyed, by highlighting main basic ideas, original design solutions, main results, and positioning in the innovation landscape. Then, current and future research trends are outlined in order to draw evolution scenarios of measurement systems for cryogenics monitoring.

1. Introduction

Temperature affects processes and material properties more than any other variable, such as pressure, magnetic field, electric field, and so on [1]. Since the mid-1800s, scientists have exploited extremely low temperature to enhance mechanical and physical properties of materials [2]. The range of very-low temperature is referred to as *cryogenics* [3]. Even if not specifically defined in literature with large agreement, in general, applications at temperature less than about 120 K are referred to as cryogenic [3]. Typical cryogens used to reach these temperature ranges are: liquid nitrogen, oxygen, helium, methane, ethane, and argon.

By analyzing spacecrafts returned from the cold vacuum of space, NASA engineers discovered that many of metal parts became stronger than before their permanence in the space just owing to their exposition to extremely low temperatures [2]. The treatment and use at very-low temperature of a wide variety of materials [4], such as metals, alloys, polymers and so on, aimed at enhancing their mechanical and electrical properties, even temporarily, are defined as *cryogenic process*. These processes are more and more exploited in several application fields, from scientific research to daily clinical medicine [5] (Fig. 1): (i) chemical reactions, in order to produce active ingredients for popular drugs (medical applications), (ii) Magnetic Resonant Imaging (MRI), to cool superconducting magnets used to provide the magnetic field, (iii) cooling systems for chemical reactors, (iv) freezing of foods and biotechnology products (vaccines), (v) cryogenic fuels, oxygen and hydrogen, used for spacecrafts, (vi) processes to enhance the electrical characteristics of electronic devices, and (vii) several physics experiments, such as gravitational wave detectors [6,7], superconducting particle accelerators, and colliders [8] and particle detectors. In industrial applications, cryogenics is exploited for [5]: freezing food [9], pressurization of plastic bottles and aluminum cans containing drinks, maintenance of pipelines by freezing the liquid on both side of the leak, ground freezing, to allow tunneling operation in wet unstable soils, heat treatment of metals [10], freezing of explosives to make them temporarily harmless, and cryo-cleaning. In biological and medical fields, cryogenics is used to enable biological material to be frozen and stored [11], especially for semen [12], thin tissues, and blood. Furthermore, the use of superconducting magnets allows detecting abnormalities of various tissues of the body, using MRI techniques [13]. Liquid hydrogen is used together with liquid oxygen as fuel for space vehicles.

In all these application fields, a prominent role is played by the objectives of the measurement systems: to provide accurate measurements for feedback in the process control systems, and to collect information for monitoring the physical properties of materials during the cryogenic process. These measurements are carried out by means of transducers: at cryogenic temperatures [14,15], if applied directly inside the cryostat; at environmental temperature, when measuring

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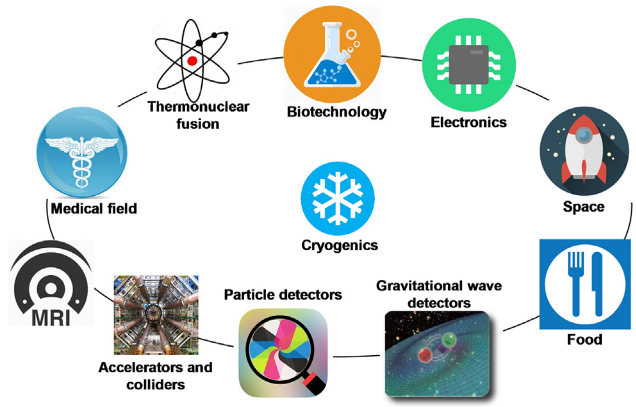

Fig. 1. Main application fields of cryogenics.

physical quantities related to the cryogenic process out of the cryostat [5]; or at both environmental and cryogenic temperatures [16], for measurements in a wide range of temperatures, e. g., during the cryostat freezing.

The main quantities generally measured in cryogenic processes are (column *Measurand* of Fig. 2: (i) liquid level, (ii) flow rate, (iii) pressure, (iv) temperature [17], and (v) electrical current.

The analysis of the scientific literature remarked that the measurements and transducers for quantities observed for the process control have received a deeper attention by the researchers. This is mainly due to the higher precision needed in order to achieve a precise control of the process.

Among these, temperature transducers used in cryogenic environment have been widely investigated [18]. In this case, specific sensors have been designed to operate in harsh environment and to assure: industrial robustness, thermal coupling of the sensor through its own wires, temperature measurement not depending critically on the installation work, and compatibility with large-series fabrication techniques [19]. Moreover, transducers have been extensively verified against environmental effects, such as the presence of heavy radiations [20] and thermal cycling [21].

On the counterpart, less research efforts have been devoted to quantities commonly observed for monitoring and diagnostics. However, with technical advancements, systems become more and more complex; thus the attention on monitoring and diagnostics increases with the interest in developing research on quantities less investigated in the past, such as pressure, flow, or level. Particular interest takes on flow measurements which, if deployed along the plant as a whole, could allow the distribution of the thermal loads to be optimized, thus both improving the efficiency and reducing the cryogenic power consumption.

Therefore, this paper is aimed at describing the state of art, as well as at drawing the current directions of the research on measurements and transducers for cryogenic process monitoring in their different application fields. The scientific literature about the design and characterization of the transducers mainly used for monitoring cryogenic processes will be discussed, by referring to: (i) liquid level transducers, (ii) flow meters, and (iii) pressure transducers. For each of these transducers, the physical principles, reported in Fig. 2, will be described and compared. Moreover, the technical solutions adopted will be presented.

The review contained in this paper does not intend to be exhaustive

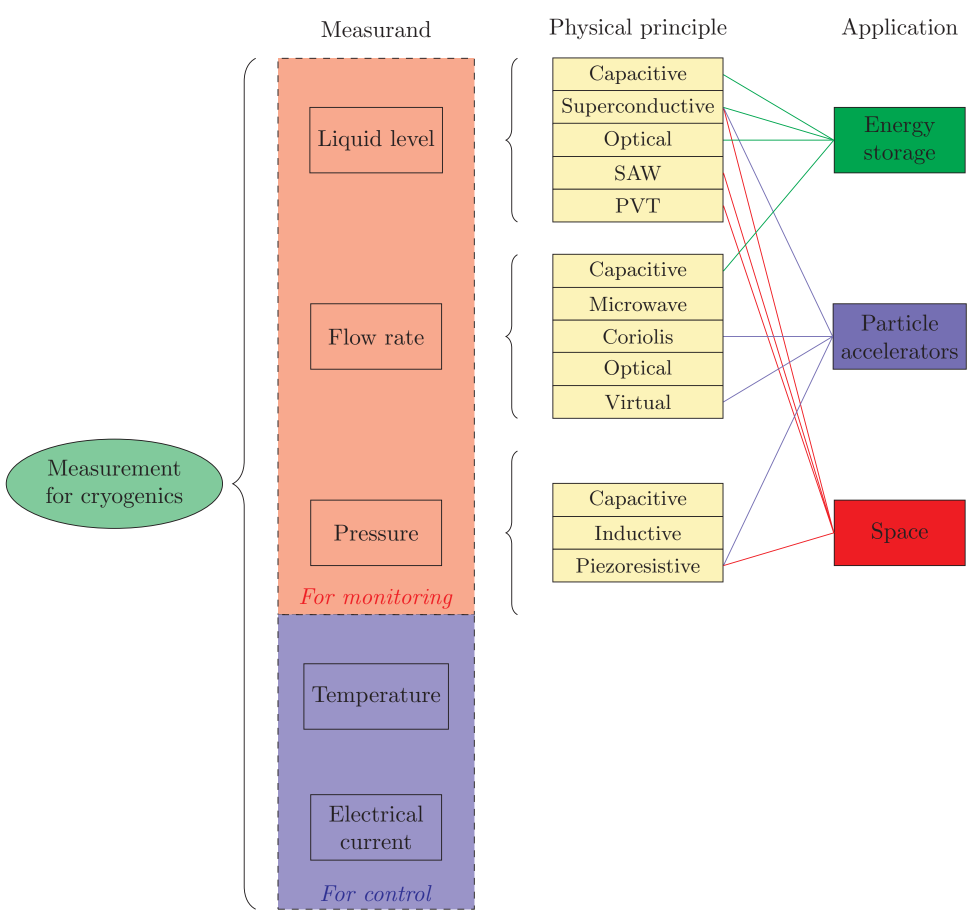

Fig. 2. Measurements for cryogenics: Measurands are classified according to the use of the measurement system for monitoring or control. Among monitoring measurements, the most widely physical principles are reported and related to the applications.