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Cryodiagnostics of SC-accelerators with fast cycling superferric magnets

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Abstract

The report concerns resistive temperature sensors, their calibration system and features to mount these sensors; RF-void fraction sensors and set-up to calibrate them; a discrete level-meter based on a resistive temperature sensor; and two-phase helium flow-meters. A way to produce a multi-channel measuring system is proposed to be applied for superconducting accelerators like FAIR-SIS100 and NICA. It is also shown that the experience obtained in cryo-diagnostics allows one to produce the separation less flow-meters for the three-phase oil-salty water-gas flows which are typical in the oil production industry.

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1. Introduction

Test benches for superconducting magnets and complete accelerator modules such as FAIR-SIS100 [1] and NICA [2] require a system to measure a lot of signals from temperature, pressure and level sensors. In addition, since the fast cycling superferric magnets [3] are cooled with forced two-phase helium flow, it is necessary to have information about its quality and mass-flow rate. For example, two-phase flow meters, mounted in return two-phase helium headers, are needed to determine the corresponding mass-flow rate as well as the quality and distribute the flows between the neighbouring refrigerators of the discussed accelerator systems [3]. The aim of this work is to choose suitable sensors and measuring devices mentioned above and offer a prototype of the measuring system to operate with a large number of sensors.

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2. Temperature sensors

In our practice we have applied three types of temperature sensors: the Rhodium-Iron Resistive T-sensor (RIRT-1) of VNIIFTRI [4] – for precise measurements in the range from 1.5 to 373 K, the composite carbon-aluminium oxide TVO-sensor [4-6] manufactured in 1990-1991 – for routine measurements in the same range, and the thin film Pt1000-sensor model C420 of Heraeus Sensor Technology – for radiation shields in the range from 20 to 373 K. In particular, the TVO-sensors prepared by us are used in the W7-X project [5]. The choice of TVO-sensors for the XFEL-project is presented in [6] where Cernox (Cx1030), TVO, CRT (carbon glass) and TTR (thin film Germanium) sensors were compared. The TVO and Pt1000 model C420 sensors can be also used for FAIR-SIS100 and NICA projects. Rather high radiation resistance of the TVO-sensors under gamma irradiation and fast neutron fluence and their predictable characteristics under magnetic fields are presented in [6-8]. As for Pt1000-sensor model C420, it has good long term stability, however its calibration curve DIN EN 60751, class B, is not so good for cryogenic temperatures – $\delta T = \pm 1.3$ K at 73 K. So we have found a united calibration curve for them: its deviation does not exceed ±0.5 K for the range from 30 to 323 K, and it is valid for all the sensors from the batch after some selection.

One of the problems while operating with temperature sensors is to avoid big errors when the sensors are mounted on a cold surface in vacuum environment like for the XFEL, NICA and FAIR projects. It is described in [6] how to solve this problem. One of the requirements is to provide the same conditions both while mounting the sensors at accelerator modules and during the calibrating procedure. In addition, for the place of mounting T-sensors, one needs to provide reliability, low thermal resistance, high electric insulation resistance, radiation resistance, minimum points of soldering, to find or produce a suitable four-lead cable and use the same grease as during the calibration procedure.

The calibration system for T-sensors is presented in [9]. A feature of this 17-channel device is that the calibration is carried out from 1.5 to 323 K with the comparison block in vacuum. The calibration scale is ITS-90 that is confirmed by the corresponding certificate. Values of temperatures were obtained by comparison with the RIRT-1 sensor whose accuracy is ±1 mK for all the T-range [4].

3. Void fraction sensors and two-phase flow meter

Cryogens are dielectrics, so to measure void fraction, $\varphi = A_g/(A_g + A_l)$, one can use sensors sensitive to the mean dielectric permittivity, ε, of the medium, $\varepsilon = \varepsilon_g \varphi + \varepsilon_l (1-\varphi)$, where A is a cross-sectional area, subscripts "l" and "g" refer to liquid and gas. To find $\varepsilon(\varphi)$, the radio frequency (RF) technique is used when the investigated media fill the volume of a resonator connected to an oscillatory circuit. By measuring the resonant frequency, *f*, of the electric oscillations in the circuit, it is possible to determine the degree of resonator filling with a relatively high accuracy. A novel practical realisation of this method to measure the void fraction of the two-phase helium flow in a round tube of ID=38 mm is presented in [10]. The calibration system for void fraction sensors is presented in [9]. A method to calibrate RF-sensors at different temperatures of saturation is described in [10]. It allows one to obtain calibration relations for a relatively wide range of temperatures, for example, from 1.5 to 5 K.

In principle, there was a problem in cryogenics to find the mass-flow rate of a two-phase flow for the whole range of quality, x, from 0 to 1. It is shown in [11] that it is preferable to use a cryogenic two-phase pressure-drop flow-meter for this aim: it is a combination of an RF-void fraction sensor of a round cross-section and a cone narrowing device. In this case the mass-flow rate, G, for arbitrary flow pattern can be found as $G = k(\varphi, T)\xi\sqrt{\Delta P \rho}$ where ΔP is a pressure difference across the narrowing device, $\rho = \rho_g \varphi + \rho_l (1 - \varphi)$ is an average bulk density, a factor ξ is a constant depending on the geometric parameters of the narrowing device, and $k(\varphi, T)$ is a correction factor depending on the flow pattern of the two-phase flow. The k-function for different flow patterns of the horizontal two-phase helium flows is estimated in [11]. To avoid decreasing the flow rate during the cool down process, the two-phase flow-meter with the narrowing device can be installed with a bypass line supplied with an open/close valve.

4. Pressure sensors and discrete level-meter

To measure pressures, we have tested two types of absolute and differential pressure sensors: Saphir22-MPS and Endress & Houser with standard output signals of 4-20 mA. Both types of P-sensors have demonstrated relative deviations of $\delta P/P \leqslant 0.25$ % suitable for practice.

The principle to measure a level of a cryogen could be based on a noticeable difference in heat transfer characteristics of a resistive temperature sensor surrounded with gas or liquid. A rule of the discrete level meter can be manufactured with, for example, 16 non-calibrated TVO resistors and a cold multiplexer to decrease the number of wires entering into the cold volume. An advantage of this level-meter is that it does not require calibration while working with any cryogen at different pressures, and one needs only a 6-pin wire connector at the cap of the cryostat. The accuracy of measurements can be of ±2 mm for the horizontal location of the TVO resistors and ±3 mm for the vertical one. The used design of modular industrial computer allows one to produce a 2-channel level-meter electronic board [12].

5. Multichannel measuring system

There are some ways to create a prototype of the measuring system to operate with a big number of sensors and devices mentioned above. One of them is to use a schematic of a multichannel system based on a modular industrial computer, MIC, with ISA or PCI bus, for example. To realize this variant, one needs several electronic boards to measure signals of different sensors. They can occupy MIC's slots from 1 to 4 for a 15-channel temperature monitor, a 4-channel pressure monitor, a 2-channel discrete level monitor and 1-channel void fraction monitor [12]. The 5-th slot is intended for the 8-channel digital to analog output board to provide a data acquisition system with standard output signals of 4 to 20 mA, 0 to 5 V or –10 to 10 V. By means of this board the chosen values of T, P, L, φ and G can be transferred to the corresponding analog signal. The details can be found in [12].

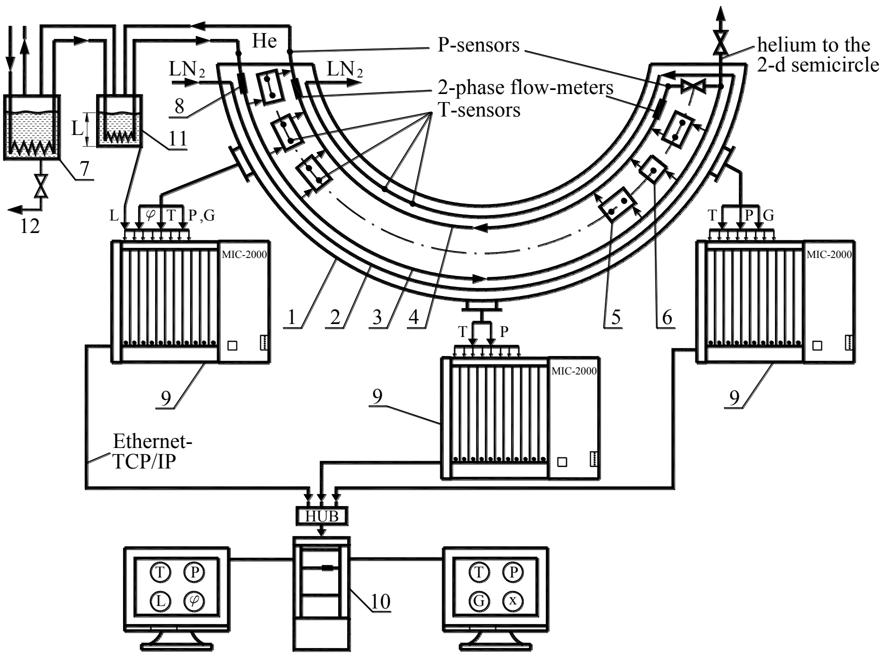

Fig. 1. A simplified version of the cryodiagnostics system for a SC-accelerator like the Nuclotron: 1 – vacuum shell of the 1-st semicircle of the accelerator, 2 – nitrogen radiation shield, 3 – header to feed LHe flow, 4 – return header of two-phase helium flow, 5 – dipole SC-magnet, 6 – quadrupole SC-magnet, 7 –vessel for LHe of the refrigerator, 8 – mass production single-phase flow-meter of Coriolis type, 9 – 11-slot modular industrial computer , 10 – server, 11 – subcooler, 12 – LHe transfer line to the neighboring refrigerator.

The 6-th slot is used for a standard CPU-board supporting the SVGA, PS/2, USB, RS232, RS485 and Ethernet interfaces [12]. For example, the dimensions of the 6-slot MIC with ISA bus are 175□190□285 mm3. To enlarge the system, a MIC with bigger slots or several MICs can be connected to a server via Ethernet with TCP/IP protocol.

An example of the multichannel measuring system for a SC-accelerator is shown in Fig. 1.

6. Application of cryogenic technologies for oil production industry

Similar but significantly much more complicated diagnostics problems with respect to two-phase cryogenic flow-meters arise in the oil-producing industry while determining the outflow of oil wells, where three-phase “oil-formation water-gas” flows occur. Cryogenic technologies are worth applying in this branch of industry, because the temperature here can vary in a wide range from 213 K (–60°C) to 323 K (+50°C).

To perform full diagnostics of the three-phase flow, the number of independent signals from sensors should be equal to the number of unknown parameters. Assuming that the velocities of the phases are equal and the salinity of the formation water is constant, there are three parameters of the “oil-formation water-gas” flow: the volume fraction of gas, φ, the volume fraction of water or water-cut, w, and the total mass flow rate, G. Therefore, it is necessary to measure at least three independent signals from some sensors.

These sensors can be an RF-sensor of a round cross-section whose resonant frequency depends on the average permittivity of the flow, ε, a narrowing device which gives a value of a pressure drop, ΔP, depending on the average flow velocity, v, and a correlator based on a pair of the two RF-sensors to determine the correlation time, τc, and average density, ρ. Such measuring system was designed, produced and tested. Features of hydrodynamics and electrodynamics for “real oil-formation water” mixtures and good experimental results are shown in [13].

The scheme of a three-phase flow-meter and test results are shown in [14]. This system operates rather well in the range of $w \approx 0$-60 %. To provide ability to work in all the w-range, a combination of a spectrometric two-channel gamma-densitometer and a combined narrowing device was used in the last version of the separation less three-phase flow-meter. The characteristics of this flow-meter were studied on the Russian State Special Primary Standard of the Unit of Mass Flow Rate of Gas-Liquid Mixtures GET195-2011. A preliminary analysis has confirmed the operability of the flow-meter, definiteness of its characteristics and their repeatability in all the ranges of the preset parameters for such mixtures as “oil emulator-water”, “oil emulator-gas” and “water-gas”.

If to use the 1-channel Cs-137 gamma-densitometer, one can produce a two-phase “oil-formation water” flow-meter. Good test results for this device are demonstrated in [15]. Such an approach can be also used for LNG two-phase flow-meters with the liquid-to-gas density ratio $(\rho l/\rho g) \leq 30$-35.

7. Conclusion

The described multi-channel cryo-diagnostics system provides full information about horizontal two-phase helium flows, allowing one to measure and find values of temperatures, T, pressures, P, void fractions, φ, qualities, x, and mass flow rates, G, for all the range of void fractions. It can be used for superconducting accelerators with fast cycling superferric magnets as NICA and FAIR-SIS100. Its separate sensors and measuring devices could be used for other cryogenic applications.

Cryogenic technologies were used to design and produce three-phase “oil-gas-salty water” flow-meters. A new three-phase flow-meter is based on the spectrometric two-channel gamma-densitometer and combined narrowing device. Experimental tests have shown that its application seems to be rather optimistic for all the ranges of water-cuts and gas void fractions.

In addition, one can produce water-cut meters and two-phase “oil-salty/formation water” flow-meters for the range w=0-100 % using gamma-densitometers. A two-phase flow-meter for LNG can be also produced as a combination of a gamma-densitometer and a narrowing device.

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