Milsch, H., Giese, R., Poser, M., Kranz, S., Feldbusch, E., Regenspurg, S. (2013): Technical paper: FluMo - a mobile fluid - chemical monitoring unit for geothermal plants. - *Environmental Earth Sciences*, *70*, 8, 3459-3463,

DOI: 10.1007/s12665-013-2408-x

Environmental Earth Sciences

Technical Paper: FluMo - A mobile fluid-chemical monitoring unit for geothermal plants

--Manuscript Draft--

Manuscript Number:	ENGE-D-12-00901R3
Full Title:	Technical Paper: FluMo - A mobile fluid-chemical monitoring unit for geothermal plants
Article Type:	SI: GeoEnergy
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Response to Reviewers:	In agreement with the remaining editorial reviews by reviewer #3 and #4 the title of our paper has been changed and the references have been checked and updated.

Technical Paper: FluMo - A mobile fluid-chemical monitoring unit for geothermal plants

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Abstract

A versatile fluid-chemical monitoring unit has been developed in the framework of the geothermal research platform Groß Schönebeck, Germany. It enables selective online and in situ measurements of various physico-chemical parameters at different surface locations of a geothermal fluid loop. Sensors are provided for pressure, temperature, volumetric flow-rate, density, pH-value, redox potential, oxygen content, and electrical conductivity. Additionally, the apparatus features two fluid samplers to manually collect fluid under in situ conditions and ultimately analyze the solution composition. All devices are mounted on a rack allowing easy transfer of the apparatus to other geothermal plants. The maximum operating pressure and temperature of the unit are 15 bar and 150°C, respectively. The scientific and technical purpose of the system is to monitor a compositional variability of the produced fluid and chemical processes potentially occurring within the plant. These may result from reactions between the fluid and the surrounding materials, e.g. corrosion. Also, mineral precipitation as a consequence of temperature and/or pressure decrease or oxygen contamination may occur. This information is of paramount importance as so induced reactions might lead to failure of plant components or may damage the geothermal reservoir upon fluid reinjection and thus decrease injectivity.

Keywords

geothermal energy, geothermal brine, geochemical monitoring, fluid, scaling, corrosion

Introduction

The sustainable development and use of geothermal sites, particularly those within sedimentary basins, faces severe challenges due to often highly saline fluids additionally containing an abundance of other dissolved ionic species (e.g. Huenges et al. 2010). An example of such systems is the geothermal research platform Groß Schönebeck, at approximately 60 km northeast of Berlin, Germany. At this site within the Northeast German Basin (NGB) a geothermal doublet has been installed accessing a Lower Permian sandstone reservoir at approximately 4300 m depth (Moeck et al. 2009). Within the reservoir section in both wellbores stimulation treatments have been performed to enhance productivity (Enhanced Geothermal System, EGS) (Zimmermann et al. 2010). Reservoir and wellbores were complemented with technical components on the surface (e.g., a gas separator, coarse and fine filters, and an injection pump) as well as an Organic-Rankine-Cycle (ORC) binary power plant (Frick et al. 2011).

At reservoir depth the temperature and pressure of the geothermal fluid are approximately 150°C and 45 MPa, respectively. The fluid itself is a highly saline basinal fluid of Na-Ca-Cl type containing 265 g/L of total dissolved solids (Regenspurg et al. 2010). In addition, the fluid contains around 1 Nm^3 of dissolved gases, mainly N_2 (ca. 85 vol%), CH_4 (ca. 14 vol%), and CO_2 ($\leq$ 1 vol%). The principal ions in this fluid yielding a corrosion and scaling (mineral precipitation) potential, respectively, are Cl and Sr, Ba, Ca, Fe, Mn, Zn, Cu, Pb, Si as well as SO_4 and HCO_3. During production, heat extraction, and reinjection the fluid undergoes severe changes in its thermodynamic pressure and temperature state inducing supersaturation of a number of mineral phases (e.g. barite and anhydrite). Electrochemical processes provoke deposition of native metals (e.g. Cu and Pb). Potential oxygen contamination may trigger oxide or hydroxide formation (e.g. of Fe and Mn). Finally, accidental degassing of CO_2, normally maintained in solution throughout the thermal loop, may yield carbonate precipitation (e.g. calcite).

For both sustainable operation of the plant and related scientific research a comprehensive physico-chemical and compositional fluid variability has to be monitored at in situ surface conditions. The extrapolation of this data to down-hole in situ conditions is not straight forward. However, surface monitoring will allow tracking the overall chemical evolution of the fluid as production progresses. Most importantly, it will permit to investigate temperature dependent scaling processes occurring within the surface installations, e.g., the heat exchanger. Not least, reactions of the fluid with the surrounding materials, e.g. corrosion processes in the pipes, can be resolved in time and space.

There might be examples of monitoring systems from the oil and gas or chemical industry. These systems, however, are either not commercially available or do only consider particular parameters. A commercial device designed for use in geothermal plants and fulfilling the tasks mentioned above, to date, is not available. In the framework of the geothermal research platform Groß Schönebeck a mobile fluid-chemical monitoring unit ("FluMo") has been developed for this purpose. In the next section, the implementation of the system into the surface installations will be outlined. Subsequently, the individual components of the device will be described. The concluding section then highlights some first experiences related to the technical performance of the unit and finally gives an outlook on potential future upgrades regarding the analytical capabilities of the device. Complementary scientific results on changes in physico-chemical fluid properties so obtained are presented in a companion paper (Feldbusch et al. 2013).

Implementation of the system

Before starting the setup a number of requirements were defined regarding the technical capabilities the system should have. (1) Measurements should be possible on the surface at various locations of the plant. (2) Measurements should be possible simultaneously for a number of defined physico-chemical parameters. (3) Data should be acquired and saved automatically. (4) Fluid sampling should be possible under in situ conditions in parallel to the measurements. (5) Despite economic compromises to be made the fluid wetting parts of the system should be selected as corrosion resistant as possible. (6) The device should be mobile to allow transport and installation at other geothermal sites.

The ports from which fluid is tapped were defined along the main fluid line on the surface in connection with the various installations outside and within a hall. Fig. 1 illustrates these locations labeled A through G and R. Port A, outside the hall and close to the production well, serves only for fluid sampling. Ports B through G refer to the locations inside the hall before the degasser, after the degasser, before the coarse filters, before the power plant, after the power plant, and after the fine filters, respectively. At port R the fluid is fed back into the main line.

On the main line the ports consist of horizontal DN 50 / PN 40 T-flanges with a 1/2” tube connector complemented each with one electrical ball valve and one manual plug valve for additional safety. From there, a combination of flexible PFE-lined high pressure hoses and 1/2” 316L stainless steel tubing, both isolated, are guided to the permanent location of the device within the hall. The six fluid lines from ports B through G are then connected to the device individually. Identically, from the unit’s outlet, the fluid is guided back to port R on the main fluid line. In addition, electric cables installed along the tubing allow centralized and remote control of the ball valves from the monitoring system. Fig. 2 illustrates these connections and the individual components of the unit’s flow-through line detailed in the following section.

Components

Components on main line

The following two components are external installations but are related to the monitoring system. At port A, close to the production well, a *BIAR* valve-bayonet system is installed permitting oxygen-free in situ fluid sampling into a PN 40 *Hastelloy C-22* container with 100 ml volume. Inside the hall, close to point B, a toroidal inductive *Endress+Hauser* PEEK electrical conductivity-probe is vertically inserted into the main fluid line.

Rack overview

The monitoring device itself is devised as a flow-through line as illustrated in Fig. 2. All components are mounted on a movable rack and are arranged at three different levels as shown in Fig. 3. The upper level holds the control and data acquisition system. In the center, all sensors and analyzers as well as two fluid samplers are installed. Finally, at the bottom level, the pump driving the fluid and a cooling circuit is located. The six fluid lines described above enter the device through a 316L 7-port stream-select system with electrical actuators. The seventh port serves for optional fluid release and can also be used for flushing the system. All components of the flow-through line are connected with 1/2” 316L stainless steel tubing. Safety features of the device include an emergency stop switch, a pressure-adjustable relief valve with handle, an electric pressure gauge, a plug valve at the fluid outlet as well as an additional check valve at port R (Fig. 2). Tubing layout and physical limitations were defined by the minimum/maximum flow rate of the density meter (100-500 L/h), the desired fluid velocity at the pH-probes (1 m/s), and the maximum pressure rating of the flow-through cells (10 bar). Temperature limitations are sensor dependent and are described in the next subsection.

Sensors and fluid sampling

From the stream-select system the fluid first passes a *BIAR* sampling system as described above to collect fluid at in situ pressure and temperature. Then, an *Endress+Hauser* PFA-lined flow meter is installed into the line. After the subsequent *Anton Paar* density meter with a *Hastelloy C-276* vibrating tube and an integrated Pt100 thermo-sensor the fluid pressure is reduced from the one in the main line (≈ 15 bar) to 10 bar by a first pressure regulator with up- and downstream analog manometers. Afterwards, the fluid enters the first flow-through cell to measure pH-value and redox potential. Commercially, no pH-probe was found to be available covering the temperature range of interest between approximately 150°C and 70°C, which are the upper and lower temperature margins for production and injection, respectively. Therefore, at the high temperature side in flow-through cell 1, a ZrO_2-based pH-probe is installed complemented with a platinum redox-probe working against the same external pressure balanced Ag/AgCl reference-probe, all from *Corr Instruments* with *Hastelloy C-276* insertion tube. In addition, a Pt100 thermo-sensor is inserted into the flow-through cell from below. This solid state pH-probe only operates properly at temperatures above approximately 90°C. Consequently, for lower temperatures, another type of pH-sensor had to be selected. To cope with individual specifications of the probes in flow-through cells 2 and 3 the fluid has to be cooled by means of a circuit outlined after the next subsection. In flow-through cell 2 *Endress+Hauser* pH and redox glass-based electrodes, both with Ag/AgCl internal reference and the pH-sensor additionally with an NTC-thermistor, are installed. Set in parallel, a third flow-through cell accommodates an *Endress+Hauser* oxygen-probe with a titanium insertion tube and an integrated Pt100 thermo-sensor. Flow at reduced rate through this cell is accomplished by an 1/8” 316L stainless steel capillary and a second pressure regulator behind cell 2 to decrease pressure by approximately one bar. At the upstream side of cell 3 the capillary is coiled to allow the fluid to cool further from the temperature level behind the cooling circuit, e.g. 70°C, to 50°C as suggested for this probe. After the junction of flow-through cells 2 and 3 a second *BIAR* sampling system is installed to collect fluid from the low temperature side. Finally, the fluid is pumped back into the main line by means of a frequency controlled *Verder* gear pump with 316L stainless steel pump housing and PEEK gear wheels.

Sensor maintenance and calibration

Maintenance and calibration of the analytical devices is performed in agreement with the specifications made by the respective manufacturers. In particular, this concerns the electrical conductivity-probe mentioned above, the flow meter, the density meter, and the oxygen-probe. The redox-probes in flow-through cells 1 and 2 are calibrated with 220 mV/pH 7 reference solutions. The *Corr Instruments* pH-probe in flow-through cell 1 provides a mV-signal that is calibrated at 95°C with pH 4, 7, and 10 buffer solutions and, in addition, against the *Endress+Hauser* glass-based pH-probe in flow-through cell 2. The latter is calibrated beforehand with pH 4 and 7 buffer solutions using the procedure provided by the *Endress+Hauser* pH signal analyzer. Additional corrections for temperature and salinity are applied on the raw pH-data as outlined in Feldbusch et al. (2013). The calibration of redox and pH-probes is repeated on a weekly basis.

Cooling circuit for active fluid temperature control

Between flow-through cells 1 and 2 a *GEA* 24-plate 316L stainless steel Ni-alloy brazed heat exchanger is installed connected to a temperature servo-controlled cooling circuit. For a maximum flow rate of 500 L/h the in situ temperature of the geothermal fluid can be decreased to a minimum of 60°C. Besides fulfilling the sensor requirements mentioned above, this enables online scaling experiments to be conducted with this device. In addition to the heat exchanger, the main parts of this water-based cooling circuit are a *Grundfos* horizontal multistage pump, an *AirCom* motor-driven proportional valve for mixing, and an *SLB* water-air fan-type cooler. This movable cooler is placed outside the hall and is connected to the device by means of two hydraulic hoses for supply and return flow. All other components are integrated directly into the rack of the monitoring unit (Fig. 3).

Control and data acquisition

Both control of the device and data acquisition is performed *National Instruments (NI) Labview*-based from a 17” panel PC-system installed in the upper front part of the rack. Electronic hardware, also, is *NI*-based and processes the incoming 4-20 mA signals from the various analyzers of the analytical devices. In addition, this hardware allows remote control of the ball valves, individually or jointly, on the main fluid line in the hall and the stream-select system at the device. Data acquisition is performed on a temporary storage basis with onscreen data display and FTP data transfer to a server located at the GFZ-Potsdam. Finally, an *ONLINE* 1000 W self-contained power supply is installed to avoid data loss and to maintain control of the apparatus and valves in the event of power failure.

Summary, performance, and outlook

In the framework of the geothermal research platform Groß Schönebeck, Germany a mobile fluid-chemical monitoring unit (“FluMo”) has been developed. Fig. 3 on the right shows a photograph of “FluMo” as actually installed, connected, and operational within the hall at this site. Visible on the front side of the apparatus from top to bottom are the panel PC, the individual analyzers of the analytical devices, the two fluid sampler valves including the bayonet connector for the sampling container, and finally the two pressure regulators. Located on the right from top to bottom are the self-contained power supply, the three flow-through cells containing the pH, redox, and oxygen-probes, the 7-port stream-select system, and finally the safety relief valve.

The system proved to be free of leakage even after having been maintained fully filled with geothermal fluid during winter time at -20°C for several weeks. Functionality of the device including the cooling circuit showed to be excellent. During a week-long fluid circulation test “FluMo” continuously monitored the evolving fluid properties (Feldbusch et al. 2013). It showed that all sensors with the exception of the low temperature pH-probe in flow-through cell 2 worked properly and delivered consistent results. Several other types of commercial pH-electrodes have been tested since with none totally satisfactory but at least one, internally pressurized to 6 bar, with a lifetime of approximately 210 h.

Finding the optimum pH-probe will continue to be an ongoing issue and very likely a matter of future research and development. In addition to improving classical techniques, solutions based on fiber-optics and/or spectrometry might be an option. This technique has been successfully applied for pressure and temperature measurements at elevated pT-conditions (Reinsch et al. 2013). Ongoing research, e.g., addresses the applicability of dyes in fiber-optic sensors to measure pH. Ultimately, the monitoring unit outlined here could help evaluating new sensors and techniques and can also be expanded in analytical capabilities with additional flow-through cells, e.g., for ion-selective electrodes, with an inline viscometer, and/or with a combined density-sonic velocity device.

Acknowledgments

The authors thank Andreas Kratz and Tanja Ballerstedt for substantial technical support. Discussions with Wulf Brandt and Erik Spangenberg led to technical improvements and are greatly acknowledged. Constructive reviews by two anonymous reviewers helped to improve the manuscript. This project was financially supported by the GFZ-Potsdam and a grant in the framework of the German Economic Stimulus Plan II (2009).

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Figure Captions

Fig. 1 Schematic of the main fluid line and surface installations at the geothermal research platform Groß Schönebeck, Germany. Bold arrows indicate the in and outgoing fluid directions from/to the wells (1) and the power plant (5), respectively. The other numbers denote the degasser (2), an expansion tank (3), the coarse filters (4), the fine filters (6), and the injection pump (7). Arrows and letters inside the hall (B-G, R) denote the locations at which fluid can be selected for online and in situ monitoring with “FluMo”

Fig. 2 Schematic of both the fluid ports on the main line and the flow-through line within “FluMo” including the different analytical components

Fig. 3 Left: Design drawing of “FluMo” with the control and data acquisition system (1), the sensors (2), analyzers (3), and two fluid samplers (4) as well as the pump driving the fluid (5) and the cooling circuit (6). Right: Photograph of “FluMo” installed and operational at the geothermal research platform Groß Schönebeck, Germany

Figure 1

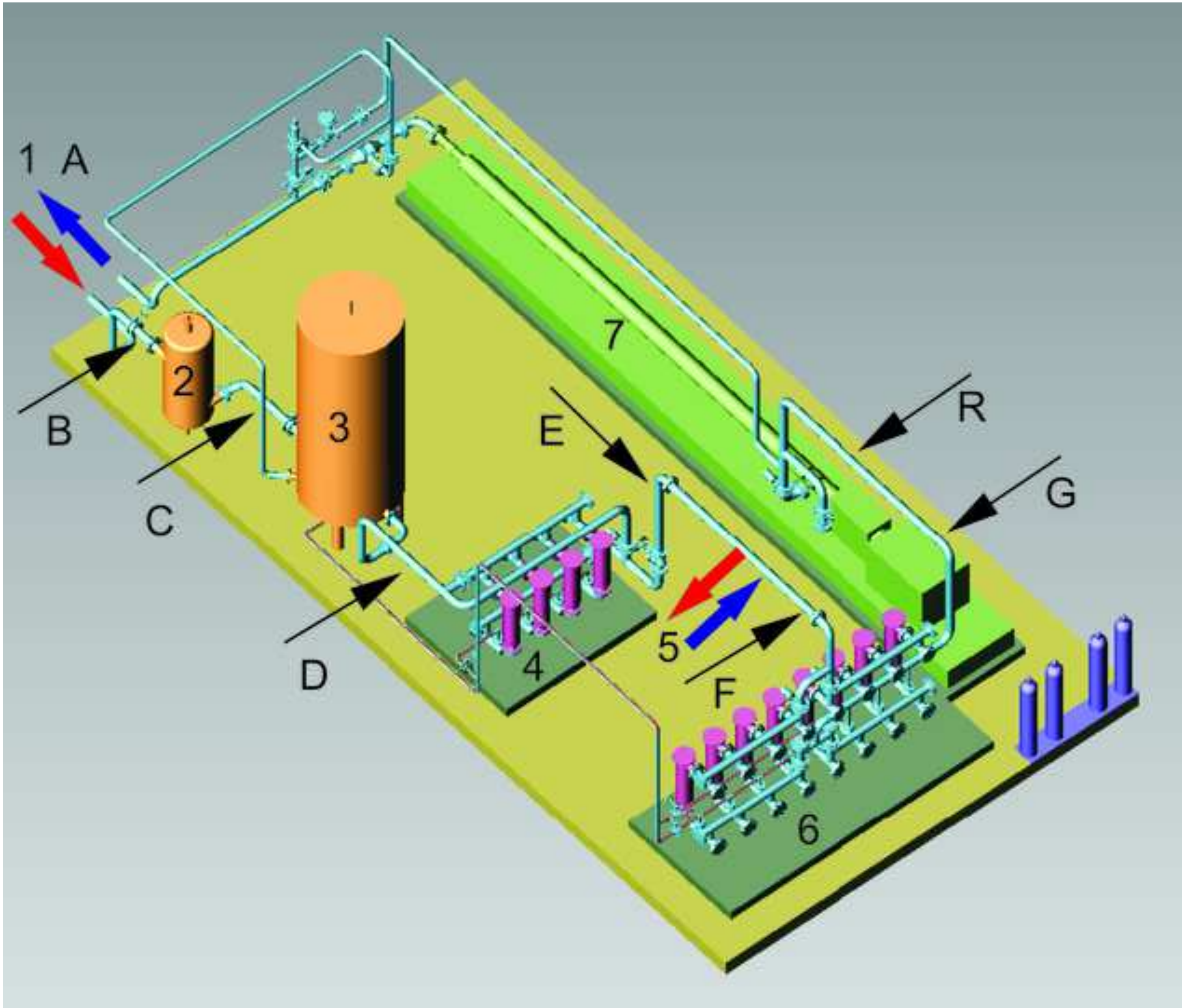

Figure 2

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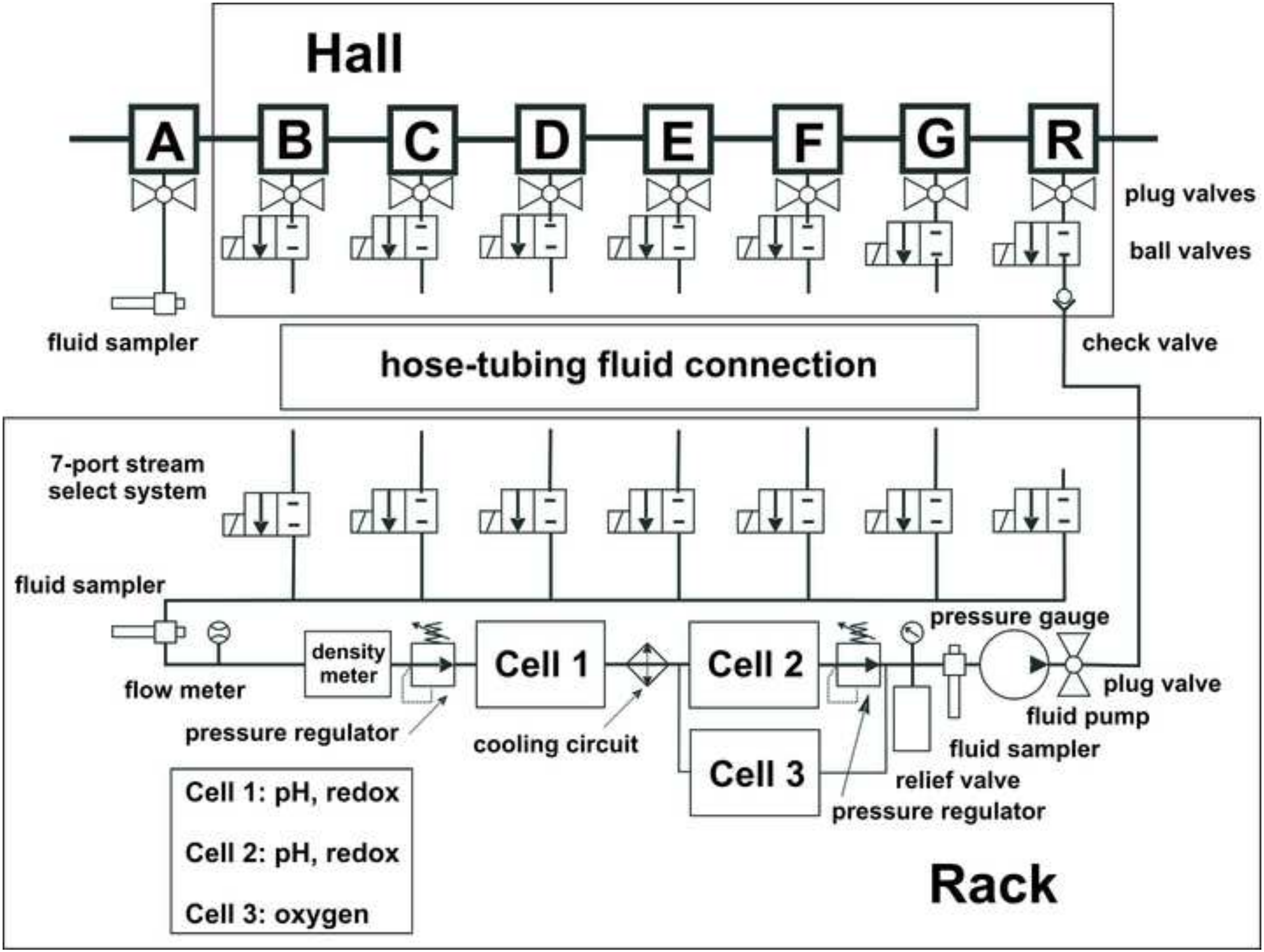

Figure 3

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