Fluid level sensors with metrological self-check function based on the concentration effect

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Abstract. This paper presents the results of the experiments on studying the properties of concentration elements, which were carried out in order to develop a new principle for measuring the level of conductive and non-conductive polar liquids, as applied to the operating conditions of nuclear and thermal power facilities. The paper includes the methods for increasing the level and stability of the useful signal of concentration elements and design solutions for creating the fluid level multi-electrode sensor. Considering the current trends towards an increase in the number of measuring channels at NPP and TPP power units and the need to optimize metrological service, it is noteworthy that the concentration effect is considered not only in terms of a new principle for measuring the liquid level, but also implementation of metrological self-check of conductometric and capacitive fluid level sensors.

1. Introduction
Some information related to concentration cells (CCs) in electrochemistry dates back to the 19th century. However, as high electromotive force (EMF) values are needed in practice, electrochemical cells with galvanic pairs and strong electrolytes are the most widely used devices. The application field of concentration cells [1-3] in industry is presently limited to conductometers, pH-meters and concentration meters, which generally have sophisticated operating principles and costly designs, for example, using calomel or hydrogen electrodes and electrolytes with diffusion barriers.

This article presents the perspectives of using concentration cells for measuring fluid level and implementing metrological self-check [4-6] of discrete-type conductometric and capacitive level sensors.

Thus in order to implement metrological self-check, an innovative concentration-based principle of measuring the fluid level is proposed [7], which has a number of advantages over the known methods and principles of level measurement used in industry. The development and possibility of implementing the newly proposed principle is based on the results of the study of properties of concentration cells that are manifested on large volumes of polar fluids and/or ion-containing fluids.

We consider in detail some of the discovered properties of concentration cells that allow implementing metrological self-checking of level sensors.

2. Some results of studying the properties of concentration cells
To study the properties of CCs, identical electrodes were alternately immersed in a cuvette with distilled water and other polar fluids in a number of experiments. “Bottled distilled water (for accumulator batteries)” with electrical conductivity of no more than 5⋅10⁻⁴ S/m, according to the...
certificate, was used as distillate. The electrodes used in the experiments were made mainly from a single conductor of copper cable in order to ensure identical composition of the electrodes. Besides copper electrodes, stainless steel electrodes were used. The majority of measurements were performed using M-830 multimeter with input resistance of 1 MOhm, allowing measuring directly the EMF of the concentration cell. A galvanometer was used in some experiments.

Figure 1 shows typical plots of the dependence of the concentration EMF on time, according to the results of one of the experiments with alternate immersion of copper electrodes in cuvettes with distillate. Reproduction and registration of the results was performed by photo-recording of the multimeter readings at maximum frequency of 10 frames/sec.

![Figure 1. Graphs of changes in concentration EMF over time.](image)

The origin and existence of EMF in the concentration cells is explained by the laws of electrochemistry. In short, the process of charge formation is as follows. Polar molecules of water interact with copper ions. Transfer of metal ions into water occurs, where hydrated ions are formed. The electrode acquires electric charge, and a double electric layer appears on the metal-water interface. The submerged electrodes acquire electric charges that are different in value because of different concentrations of hydrated ions that have formed. Then equalization of ion concentrations proceeds, causing decrease of the potential difference (i.e. EMF) on the electrodes to zero according to logarithmic laws [1–3]. In other words, such a system tends to electric equilibrium.

At a cursory superficial glance, there is nothing noteworthy in the results obtained, but this is not quite true regarding the initially formulated problem of measuring the level of fluids for the implementation of metrological self-check. In fact, the first thing that the experiments showed is that for large volumes of even weak electrolytes - polar fluids - the EMF value reaches tens or hundreds of millivolts, while the processes of EMF decrease to zero in concentration cells are very slow. For example, for distillate volumes ranging from 1 to 3 liters only, the decrease of concentration EMF to zero was not observed in the experiments lasting up to 100 hours. For distillate volume of 1 liter, only periodic transitions of EMF across zero with change of sign were observed, what is notable in itself. For test-tube volumes less than 30 ml, the decrease of EMF values to zero lasted no more than 20 minutes. Hence, it can be stated that with increase of volume of the polar liquid in contact, the inertia (sluggishness) of EMF decrease process is increased multifold.
Regarding the issue of connecting the CC electrodes to the measuring equipment, the main role is played by the following particular feature that was discovered. The polarity of the concentration EMF does not depend on the area (volume) of electrodes immersed in the fluid. The electrode that is the first to be immersed is always positive, and the electrode that is the second is negative. Subsequent removal and new immersion of the electrodes showed that the “wall-adjacent” layer of fluid directly surrounding the electrode and forming the double electron layer is a fairly stable formation. It is stable to such extent that the electrodes removed from the solution show the polarity corresponding to the first immersion during the next immersion also, regardless of the sequence of contact of the electrodes with the solution. In order to make the polarity change according to the sequence of immersion, it is necessary to dry the electrodes completely.

From the point of view of electrochemistry, the observed EMF fluctuations with long period reaching several hours are interesting. Thus, detailed mapping of the measurement results allowed to find out that such long waves in EMF changes have their own conditional “sliding equilibrium point”. As a result, it can even cause periodic change of EMF polarity. Presumably this is caused by the inertia of the processes. When several electrode pairs were immersed in the same cuvette, the EMF fluctuations on them were never synchronous. In the results obtained, not only the change of EMF polarity is interesting, but also the fact of periodic growth of EMF in absolute magnitude. A separate detailed study is required for precise description of such processes and derivation of mathematical relationships taking into account the reversible electrode potential and a number of other factors.

Other important aspects of the problem being solved are the following special features of CCs:

- EMF value of concentration cells reaches tens of millivolts in polar fluids, such as distilled water and even acetone (dielectric material);
- any movement of fluid or vibration of electrodes leads to violation of the concentration balance, causing increase of EMF and renewal of chemical reactions;
- during the entire time of electrode potential equalization, chaotic frequent fluctuations of EMF with amplitudes up to 0.3 mV are observed, along with slow fluctuations (waves) in EMF change with period up to 5 hours which can lead to change of electrode polarity;
- concentration cells are resistant to formation of dielectric oil films on the electrodes, and react on heating or cooling of one of the electrodes similar to the operation of differentially switched thermocouples;
- if the electrodes come into contact with saturated steam, no concentration EMF appears;
- under conditions of formation of fluid films between the electrodes when draining the cuvette, the concentration EMF instantly drops to zero.

Detailed results of the experiments and descriptions of the above mentioned and other special features of CCs are given in [8]. A few general conclusions can be drawn. Process tanks at NPP and TPP have huge volumes, much larger than the volumes of liquid used in experiments, so in industry the EMF will be predictably constant to be different from zero during all of time of technological process. This is also facilitated by the fact that rapid heat and mass transfers take place in technological tanks, so the liquid is constantly in motion, which violates the concentration equilibrium and increases the EMF in modulus. Thus, if the liquid level is monitored by exceeding the EMF threshold value then we can take the stable measuring. To increase the level of the useful CCs signal we apply structure such as “amplifier - limiter - rectifier - signal smoothing block - comparison block”. Smoothing can be implemented based on linear and adaptive filtering, but preferably based on the damping signal in an interval of two or three seconds. For measuring the liquid level at small volumes we apply other design [9].

For metrological self-check it is more than enough for CCs to work during one minute. This is easily achieved even with small liquid volumes. Thus, the CCs signal processing can be optimized to self-checking.

Taken together, the discovered special features of CCs allow implementing the concentration principle of measuring fluid level which ensures stable level sensor operation under conditions of single-phase and two-phase saturated media (steam-water), current-conducting fluids and polar
dielectrics, and measuring fluids in the presence of oil drains. The advantages of the concentration principle over the known measurement methods (hydrostatic, conductometric and capacitive) confirm the practicality of developing the level sensor based on this principle.

3. Ways of solving design problems in creating the level sensor with metrological self-check function

The uniqueness of the concentration principle is that only connection of a voltmeter to the electrodes of the primary converter is required for short-term level measurements. Therefore, it makes possible to combine several principles of level measurement basing on a single unified immersed probe with electrodes installed at different heights. For example, in the mode of concentration measurements, the level is recorded by the fact of presence of EMF on the electrodes immersed in the fluid, while in the mode of conductometric measurements the level is recorded by the fact of drop of electrical resistance on the same electrodes immersed in the fluid. By switching the measurement modes, it is possible to implement adaptability of the sensor to changes in the characteristics of the measured medium, and also to implement metrological self-checking. This expands the range of capabilities of the sensor and increases its reliability.

For example, if the conductometric principle [10] and concentration principle are combined to measuring of the fluid level, the following synergy appears. The concentration principle makes it possible to measure current-conductive fluids and all polar dielectrics, provides stable operation of the level sensor under conditions of formation of films of current-conductive fluid between the electrodes, formation of non-conductive oil films on the electrodes, and in presence of saturated steam and intense condensation. The conductometric principle ensures long-term operation of the CCs on small volumes of absolutely motionless liquids by means of applying current to the electrodes. Naturally, this technical solution ensures stable operation of the level sensor in different operating modes of the process equipment. Such combinations of different operating principles allow implementing the functions of adaptability and metrological self-checking of sensors.

While the task of continuous level measurement requires finding the solutions ensuring long-term and stable operation of concentration cells in motionless fluids, the task of metrological self-checking is simpler in this regard, since it does not require long-term operation of the concentration cells. The operation of concentration cells lasting for 20 seconds is more than enough to evaluate the metrological operability of the sensor and the entire measuring channel as a whole.

The design of such a sensor must meet two main requirements: the electrodes of the level sensor must be electrically isolated from each other, and the sensor housing must be hermetic. One of possible variants of the housing design that meets these requirements and provides easy assembling is shown in figure 2. The main housing of the level sensor in this solution is the tube 1 welded at the top (flange 2) and open at the bottom. In the upper part, below the mounting flange, there is a slot 3 (one or more openings) for communicating the pressure from the process vessel to the inner cavity of the housing, providing flow of fluid inside the level sensor. Threaded connections 5 and 6 are provided for installing the protective cover 4. A pass-through tube 8 (one or more) in the threaded upper flange and mounting flange is provided for feed-out of cable connections 7. The electrodes 9 are mounted in such a way that they protrude through the holes 10 in the inner cavity of the housing to ensure contact with the measured fluid. To provide insulation between the electrodes, either the housing 1 is made of dielectric materials, such as fluorooplast or caprolon, or insulation gaskets are installed in the holes 10 before mounting the electrodes.

The design of the housing shown in figure 2 reduces the hydraulic impact (the effect of dynamic pressure of the flow) on the electrodes and provides repairability of the level sensor by removing the protective cover 4. However, the level sensor must be dismantled in order to perform repair, what makes maintenance somewhat complicated. To provide repairability without dismantling the level sensor, the housing 1 can be made in the form of a bypass connected to the process tank by means of pipes with flange connections 11 (figure 3). In this case, the level sensor does not occupy volume inside the process tank, and its maintenance and repair of cable connections can be performed without dismantling.
Figure 2. Level sensor housing with internal cavity for the fluid flow.

Figure 3. Bypass design of level sensor.
The design solutions shown above are a unified multi-electrode design of the primary converter applicable for a level sensor operating on various measurement principles: concentration, conductometric, capacitive, and combined. The implementation of various suitable modes of sensor operation will depend on the capabilities of secondary multi-channel equipment. In such design solutions it is not necessary to dismantle the primary sensor during its operation in order to change (expand) the operation modes of the secondary transducer of the level sensor. Therefore, the appropriate upgrading of the level sensor can be carried out even without stopping the technologic process.

The simplicity of the concentration principle of measurement allows performing diagnostics of metrological and technical operability of conductometric and capacitive discrete-type level sensors even manually during adjustment works and maintenance. Depressurization of the tank and stopping the technologic process are not required, it is enough to connect the multimeter to the test cables from the level sensor electrodes.

Implementation of the metrological self-checking function in automatic mode allows performing remote diagnostics of the technical and metrological operability of the sensor, thus reducing exposure of operating personnel to harmful factors and saving labor efforts on scheduled maintenance.

4. Conclusion
Basing on the results of the experiments, it was found that the concentration cells, even with weak electrolytes, represent autonomous sources of small EMF with the following main special features:

- EMF of concentration cells reaches tens of millivolts even in polar fluids, such as distilled water and acetone;
- The behavior of reactions and gradual decrease of EMF in case of high-resistance load is very inertial (sluggish). For example, for distillate volumes ranging from 1 to 3 liters, the decrease of concentration EMF to zero was not observed in the experiments lasting up to 100 hours. For distillate volume of 1 liter, only periodic transitions of EMF across zero with change of sign were observed;
- Any motion of fluid or vibration of electrodes leads to violation of the concentration balance, causing increase of EMF and renewal of chemical reactions;
- During the entire time of electrode potential equalization, chaotic frequent fluctuations of EMF with amplitudes up to 0.3 mV were observed, along with slow fluctuations (waves) in EMF change with period up to 5 hours which can lead to change of electrode polarity;
- Concentration cells are resistant to the formation of dielectric oil films on the electrodes; they react on heating or cooling of one of the electrodes similar to operation of differentially switched thermocouples;
- If the electrodes come into contact with saturated steam, no concentration EMF appears;
- Under conditions of formation of fluid films between the electrodes when draining the cuvette, the concentration EMF instantly drops to zero.

These special features allow to implement the concentration principle of fluid level measurements and to implement the function of metrological self-checking of conductometric, capacitive and potentiometric level sensors. This contributes to improving the reliability of level sensors and saving labor efforts for their maintenance, thus solving topical problems of modern power industry.

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