Assessment of the possibility of developing isokinetic devices for water and steam sampling in chemical control systems of TPP and NPP

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Abstract. The proposed work is intended for operational staff and employees of project organizations. The possibility of modernization of sampling devices for superheated steam sampling in automatic chemical control systems at thermal and nuclear power plants is considered. The results of calculating the flow rate and the inlet diameter of the superheated steam sampling device are presented. A nomogram has been developed to determine the required diameter of the inlet of the sampling device. Two cases were modeled of sampling in the software package Ansys, confirming the need to modernize the design of standard devices for steam sampling.

Introduction

Currently, automatic chemical control systems are used in all units with a capacity of more than 50 MW of thermal power plants [1]. At existing power plants, the modernization of automatic control systems consists in replacing the instrument park and sample preparation devices. At newly constructed energy facilities, automatic control systems are also designed from the position of the choice of the manufacturer of chemical control devices, sample preparation devices and their subsequent placement.

Today, the implementation of design solutions for automatic control systems is typical and practically does not depend on the type of power unit. The design of automatic chemical control systems at power plants is based on the following basic principles [2]:

- organization of submission of representative samples to automatic chemical control devices and laboratory analyzes in accordance with the requirements for chemical control systems
- installation of reliable automatic chemical control devices in vulnerable areas of the steam-water tract, taking into account the requirements of the guidance documents
- maximum possible use of the existing fleet of devices and facilities for automatic chemical control at the energy facility
- use of portable chemical control devices

Based on the above principles, many projects of automatic control systems at thermal power plants have been implemented [3]. These principles do not reflect the design and development of water and steam sampling devices or the tracing of sampling lines. The significance of designing probes for water and steam is due to the contribution of the error to the measurement of up to 60% [4], which negates
the principles of reliability of the selected automatic control devices. When sampling, three conditions must be observed: the first condition is the representativeness of the sample, the second condition is the maintenance of the flow rate of at least 60 kg/hr. The third condition is that the inlet section of the probe is selected so that the velocity of steam entering it is equal to the velocity of steam in the steam line at the nominal load of the boiler.

That is why this article proposes to consider the possibility of upgrading standard probes for sampling superheated steam in relation to thermal power plants, including thermal power plants with combined-cycle plants. At the moment, it is recommended to use a tube probe for water sampling at nuclear power stations, and a slit probe with a mixer for steam sampling, which is calculated individually for each station[5]. Currently, thermal power plants with combined-cycle gas installations are being built to a greater extent, so we will next consider a CCGT with a three-circuit boiler-utilizer.

At thermal power plants with combined-cycle gas units installations, there is a problem of insufficient sampling in low and medium pressure circuits. Currently used probes are made in accordance with [6] and do not provide a flow rate in sampling lines equal to 60 kg/hr. Figure 1 shows a single-suction probe for sampling superheated steam with a sampling tube diameter of 10x2 mm.

![Figure 1. Single-suction probe for superheated steam extraction](image)

1 - bushing made of steel; 2 - 10x2 mm pipe made of steel 12X18H10T; 3 - steel tip 12X18H10T with internal diameter of 5 mm; 4 - steel plug 12X18H10T

However, it is more appropriate to use one of several types of isokinetic probes when sampling superheated low and medium-pressure steam. An isokinetic probe allows sampling in such a way that the sample enters the probe hole at the same speed as the main stream moves. This reduces the kinetic separation of suspended particles to a minimum.

In the software package AnsysFluidFlow (CFX), the process of sampling superheated low-pressure steam with a standard single-suction probe was simulated. The steam flow entered the inlet at a speed of 57.9 m/s. The change in speed along the length of the sampling device is shown in figure 2.
It can be seen that the flow has 57.9 m/s only at the time of sampling and at the time of rotation by 90°, where the acceleration of the selected medium occurs. Further speed drop is 15 m/s for the first 20 cm of the sampling line (calculated data of the software package Ansys), which contradicts the conditions of isokinetic sampling. Since the speed varies along the probe cross section, the kinetic separation of suspended particles also undergoes a change, which may affect the representativeness of the sample - the first condition for sampling is not observed. Thus, it is necessary to modernize the design of standard probes so that the flow rate in the main pipeline is equal to the velocity of the medium in the device itself, and the probe cross-section allows to achieve a sample flow rate of 60 kg/hr.

In order to detect a lack of sample flow even when sampling with isokinetic sampling devices, but with standard probe inlet diameters [6], the actual flow rate of the test medium was calculated in the low and medium pressure circuits. The object of the study was the superheated steam of the three-circuit boiler-utilizer P-133 in a combined-cycle plant. The characteristics of the superheated steam and steam pipe of a three-circuit boiler-utilizer are presented in table 1.
Table 1. Characteristics of superheated steam and steam pipe of a three-circuit boiler-utilizer

| Parameter                              | Pressure circuit |
|----------------------------------------|------------------|
|                                        | high             | medium          | low             |
| Steam parameters in the steam line     |                  |                 |                 |
| Probe type                             | Fig.1            | Fig.1           | Fig.1           |
| Mass flow rate $F_{pipe}$, t/hr        | 317.33           | 355.54          | 38.04           |
| Temperature, C˚                        | 567              | 566             | 279             |
| Pressure, MPa                          | 13.96            | 2.92            | 0.32            |
| Density $\rho$, kg/m$^3$               | 39.41            | 8.01            | 1.6             |
| Dynamic viscosity $\eta$, Pa·s         | $3,207 \cdot 10^{-5}$ | $3,134 \cdot 10^{-5}$ | $1,941 \cdot 10^{-5}$ |

The parameters of the steam pipe

| Pipe ID $d_{pipe}$, mm                | 257.3            | 574.6           | 38.1            |
| Line velocity $w$, m/s                | 43               | 47.5            | 57.9            |
| Reynold’s number in pipe $Re$         | $1,36 \cdot 10^7$ | $6,98 \cdot 10^6$ | $1,82 \cdot 10^6$ |

For each point, the actual flow rate of the sample at the entrance to the sampling device was calculated, assuming that the probe is isokinetic. The flow rate of the low and medium pressure circuits does not reach the required flow rate - 60 kg/hr, and is respectively 6.6 kg/hr and 27 kg/hr, respectively, the flow rate of the high pressure sample is excessive – about 2 times higher than the required. Moreover, excess consumption of selected steam or water may cause an elevated temperature of the test medium for device preparation of samples, if the sample preparation is not designed for flow with the sample flow above 60 kg/h, which must be taken into account as the temperature change of the sample affects the readings of the automatic chemical control and thus leads to unreliable results. The results of the calculation are presented in Table 2.

Table 2. Results of calculation of actual flow rate of superheated steam sample

| Parameter                                      | Method of detection | Pressure circuit |
|                                               |                     | high             | medium          | low             |
| Actual sampling device ID $d_{probe}$, mm     | [6]                 | 5               | 5              | 5              |
| Actual flow rate of the selected steam $Q^a_{ct}$, kg/hr | $\frac{S_{probe}}{S_{pipe}} \cdot F_{pipe} \cdot 10^3$ | 119,832         | 26,921          | 6,551          |
| Reynold’s number in pipe $Re$                 | $\frac{\rho \cdot w \cdot d_{probe}}{\eta}$ | $2,64 \cdot 10^5$ | $6,07 \cdot 10^4$ | $2,39 \cdot 10^4$ |

The obtained results of calculating the flow rate of superheated steam of the three-circuit boiler-utilizer P-133 confirm the presence of a problem in the lack of sample, which leads to violations in the operation of automatic and laboratory chemical control systems, namely, the unreliability of measurements of superheated steam quality indicators. Thus, maintaining a flow rate of at least 60 kg/h is not observed.

As one of the directions for upgrading sampling devices, it is proposed to increase the diameter of the input cross-section of the probe to ensure the required sample flow. It should be noted that the increase in the input diameter should be accompanied by maintaining the equality of steam velocities in the steam pipeline and the selection device – isokinetic selection. The results of calculating the required diameter are shown in table 3.
Table 3. Results of calculation of required diameter for superheated steam

| Parameter                                           | Method of detection | Pressure circuit |
|-----------------------------------------------------|---------------------|------------------|
| Necessary flow rate of the selected steam \( F_{probe}^{\text{neq}} \), kg/hr | Set                 | high  | medium | low   |
| Required sampling device ID, mm                      | \( \sqrt{\frac{F_{probe}^{\text{neq}}}{F_{pipe} \cdot 10^3 \cdot d_{pipe}^2}} \) | 3,5   | 7,5    | 15    |

In order to facilitate determination of the required diameter of the inlet section of the sampling device, nomograms have been developed, as a result of which the required sample flow rate is guaranteed while respecting the representativeness of the superheated steam sample due to the equality of steam velocities in the main steam line and in the sampling device itself.

Figure 3. Nomogram for determining the required diameter of the inlet section of the sampling device for a three-circuit boiler-utilizer
Colored lines indicate the three pressure circuits in the recovery boiler. To determine the required diameter of the sampling device, the line is selected accordingly depending on the contour. To determine the required diameter of the inlet section of the sampling device, the line is selected accordingly, depending on the parameters of the steam. The nomogram is suitable for thermal power plants with CCGT and thermal power plant with power boilers of any type of pressure. The difference is in the position of the colored lines depending on the pressure and temperature of the working medium.

The presented results are valid for isokinetic sampling, so we consider a typical sampling device in which the velocity of the sampled flow changes over the entire cross-section of the probe (figure 2). In order to study the lack of sample flow when using standard devices, a mathematical model of a single-suction probe in the software package Ansys Fluid Flow (CFX) was compiled. The initial data correspond to the low pressure contour of the three-circuit boiler-utilizer P-133. Steam flow with a pressure of 0.32 MPa and a temperature of 279°C was supplied to the sampler inlet. Were simulated two sampling cases with a standard single-suction probe. The first case, the flow of superheated steam at a speed of 57.9 m/s entered the inlet of the probe, it was necessary to find out what the sample flow rate is under these conditions. The second case, a flow with a flow rate of 60 kg/hr entered the inlet of the probe, it was necessary to find out the speed at which the value of the required flow rate would be feasible. General parameters of the sampled flow of superheated low-pressure steam: pressure-0.32 MPa; temperature-279°C; medium density - 1, 274 kg/m3.

Thus, in the first case of simulation, results were obtained confirming the need to upgrade standard sampling devices, since the flow rate of the superheated steam sample of the low-pressure circuit is 11.7 times lower than the required one. In the second case, to achieve the required sample flow rate of 60 kg/hr in the main pipeline, the speed must be 10 times higher than the actual speed, which is unacceptable according to the rules of technical operation.

**Conclusions**

1. The process of sampling superheated steam with a standard single-suction probe in the software package AnsysFluidFlow (CFX) is modeled. It is proved that the speed changes along the cross-section of the probe, which negatively affects the representativeness of the sample.

2. It was found that the actual sample flow rate is 12 times lower than required when using a standard probe with an internal diameter of 5 mm input cross-section, which confirms the need to increase the diameter of the input cross-section of the sampling device to ensure the required sample flow.

3. It was found that the actual flow rate of the superheated steam sample is 9 times lower than required when using an isokinetic probe with an internal diameter of the input section of 5 mm. It can be seen that the consumption of the sampled sample is 1.5 times higher than that of a standard device with the same diameter of the input section. It is noted that the diameter of the inlet hole and the speed in the steam sampling device affect the consumption of the sampled sample.

4. The required diameter of the inlet was calculated to achieve a sample flow rate of superheated steam of 60 kg/h.

5. A nomogram for determining the required diameter of the inlet section of the sampling device has been developed, which will simplify the method for determining the required diameter of the sampling device and guarantees the required sample flow while maintaining the representativeness of the superheated steam sample due to the equality of steam velocities in
the steam pipeline and the sampling device. The nomogram is suitable for thermal power plants with CCGT and thermal power plant with power boilers of any type of pressure.

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