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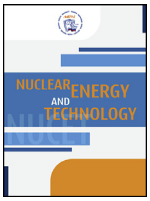

The study of ultrasonic reflex-radar waveguide coolant level gage for a nuclear reactor

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Abstract

Results of experimental study of operation of ultrasonic reflex-radar waveguide level gage in water coolant at elevated parameters with pressure up to 18 MPa and temperature up to 350 °C are examined.

In contrast to the known waveguide level gages, traveltime of acoustic pulses along the waveguide from the radiator to the subsurface layer and back is measured in the level gage under study. Waveguide consists of two acoustically isolated waveguides – the radiating waveguide and the receiving waveguide. Waveguides of zero-order flexural waves and piezoelectric transformers operated at frequency of ~800 kHz are applied. Processing of received signals is performed by microprocessor-based electronic circuit. Measurement uncertainty does not exceed ± 10 mm. Description of the experimental setup and the experimental methodology is provided.

The instrument works reliably and does not require introducing corrections of readings when coolant thermal physical properties change. The measurement instrument is intended for application in heat exchanging equipment in thermal and nuclear power generation.

Keywords: Ultrasonic reflex-radar waveguide level gage; Acoustic waveguide; Piezoelectric transformer; Water coolant operated at elevated parameters (350 °C, 18 MPa); Nuclear power installation; Power generating equipment.

Introduction

Instrumentation for control of coolant level constitutes the most vital components of control and safety systems of nuclear power installations (NPI).

Since coolant parameters examined here are practically extreme (temperature up to 350 °C and pressure up to 18 MPa at high levels of radiation) measurements of level represent a challenging technical task.

Numerous technical solutions and ideas were suggested for solving the above problem, although only small part of them was realized as working designs and even smaller fraction was practically tested.

In our opinion, acoustic instruments based on the use of metal waveguides are the most suitable type of instruments for solving the problem of water coolant level control in reactor facilities. Their application allows designing sensors with significant lifespans capable to conduct practically infinitely fast measurements and to work during extended time periods in the extreme conditions existing in nuclear power installations.

There exist two principally different optional configurations of the measurement system: the first option refers to level gages in the form of sampled data multipoint fluid signaling devices and the second option refers to the level gages allowing conducting continuous control of coolant level.

The first option is implemented on the basis of the system including several tens of waveguides each of which is equipped with piezoelectric transformer and is connected to sensitive element [1]. As the result multicomponent complex and expensive design is obtained which must be supplemented with appropriate versatile electronics and multi-wire connec-

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tion cables. Advantage of multi-point signaling devices is associated with absence of the need to perform metrological certification of the instrument.

The second option refers to acoustic impedance level gages based on the measurements of attenuation (or delay) of acoustic pulses propagating along the extended-length waveguide when the latter is submerged into fluid [2,3]. The feature of acoustic impedance level gages distinguishing them from multi-point level signaling devices is their relative simplicity and, consequently, higher reliability and low cost. Significant drawback of these instruments is their interference with output signal in response to evolutions of physical properties of the controlled medium accompanied with changes of its temperature and pressure. Additional correction of the data is needed to eliminate this interference. Interferences due to condensate flowing down along the waveguide sensitive element above the interphase boundary and due to boiling resulting in the generation of vapor-gas bubbles within the fluid phase are also possible.

The above indicated drawbacks are associated with measurement methodology based on the determination of amplitude of received signal which is influenced by different factors ranging from the resistivity of communication lines to the ageing of waveguide elements. Significant improvement of quality of the instrument can be expected with substitution of amplitude measurements of acoustic signal with time-domain measurements.

Description is given in the present paper of the originally developed design of ultrasonic reflex-radar level gage and results of its experimental studies in the conditions which are close to the maximum extent to real operational conditions with wide variation of parameters of the controlled medium, i.e. water coolant at elevated parameters.

Principles of operation and design of reflex-radar level gage

The main idea of reflex-radar level gage consists in the location of the boundary separating fluid and gas media. Transfer of energy is performed in pulsed mode along the waveguide with the measured value being the traveltime of pulses from the radiator to the receiver. Such measurement principle is implemented in superhigh-frequency reflex-radar level gages where SHF energy pulses spreading along the waveguide are used. However, application of such level gages in nuclear power generation encounters significant difficulties associated with installation of SHF devices inside equipment of the primary cooling loop.

Attempts to apply reflex-radar technology on the basis of ultrasonic waveguides were undertaken in this country during 1970s but failed to demonstrate success [4,5].

Evident advantages of waveguide level gages with measurement channel on the basis of time-domain measurements compelled researchers to revisit this idea. As the result, efforts were undertaken to develop reflex-radar level gage using ultrasonic waveguides and pulsed signals.

The following two waveguides of flexural waves (as the most efficient radiators) are applied in the proposed technical solution: namely, the radiator and the receiver of ultrasonic pulses. Waveguides are arranged vertically parallel to each other. Hemicylindrical reflector with large number of bafflers designed in the form of undulated pipe sections cut longitudinally is installed along the whole length of the waveguides. Transmission of acoustic energy from one waveguide to another can take place only when the space between the waveguides and the reflector is filled with fluid. Layout of transmission of ultrasonic wave from the radiation waveguide to the nearest to it reflector baffler under the level of fluid and then to the receiving waveguide is shown in Fig. 1.

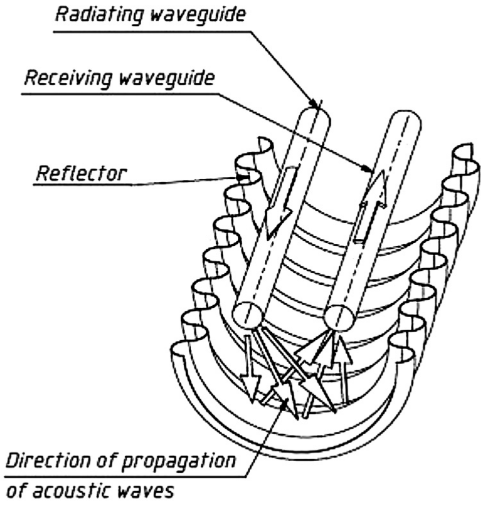

Fig. 1. Layout of propagation of ultrasonic wave from the radiating waveguide to the receiving waveguide.

Thanks to the physical properties of zero-order flexural waves efficient radiation of acoustic energy into the fluid occurs during their propagation along the waveguide submerged into the fluid. Practically complete transfer of energy of the flexural wave is achieved in the process in the contact of the waveguide with the fluid, for instance, for waveguide with diameter equal to 2 mm operated at 800 kHz frequency, along the length equal to just 30–50 mm.

Transfer of acoustic energy from the radiating waveguide in the fluid to the reflector and after that to the receiving waveguide takes place within the subsurface layer with 20–30 mm depth. Acoustic wave from the radiating waveguide penetrates the subsurface layer of the fluid in downwards direction at an angle and reaches the reflector. Following this, the wave undergoing repeated reflections from the reflector's horizontally oriented protrusions returns at the same angle in upward direction to the receiving waveguide shaping the signal on the receiving piezoelectric transformer. Fluid level is proportional to the time for ultrasonic pulses to travel along the waveguide to the subsurface layers of the fluid and back, i.e. it is determined using the time characteristic in accordance with reflex-radar principle.

Radiation of wave in the fluid takes place at the angle φ, determined from the triangle of the following sound velocities: flexural wave in the waveguide and lateral wave in the fluid [1]. For many fluids (including water) the angle at which the wave enters the fluid is approximately equal to 60°

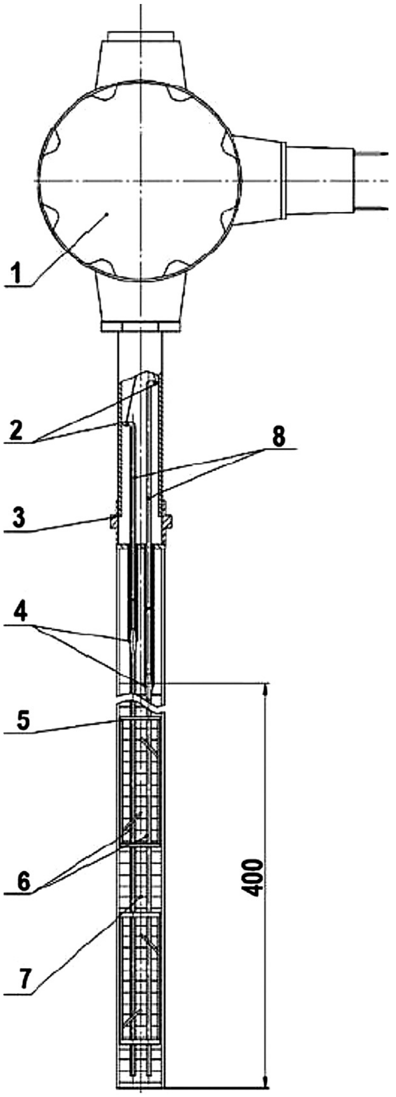

Fig. 2. Design of reflex-radar level gage: 1 – electronics unit; 2 – piezoelectric transformer; 3 – support; 4 – packing assembly; 5 – waveguide fixture; 6 – radiating and receiving waveguides; 7 – reflector; 8 – communication waveguides.

relative to the waveguide axis. Because of the polarization of flexural waves in the waveguide directional response pattern consisting of two wave packets symmetrical relative to the waveguide axis is formed in the fluid within the oscillation plane. In connection with the above, waveguides must be oriented in such a way as to obtain maximum amplitude of received signals reflected from the reflector's surface.

Level gage design includes the following components: two waveguides of flexural waves in the form of rods with 2-mm diameter and length equal to 400 mm attached through the packing assemblies to communication waveguides equipped with piezoelectric transformers of flexural waves with working frequencies of 800 kHz; hemicylindrical reflector manufactured from corrugated steel pipe with 166-mm diameter and electronics unit (Fig. 2). Suspension of parts of the instrument contains the packing assembly in the form of coupling with coupling nut, waveguide support brackets and frame for mounting the casing with electronics components.

Functional block diagram of sensor signal processing (Fig. 3) consists of the generator of video pulses, amplifier of received signals, comparator, time interval meter, digital-to-analog converter and current generator. Main elements of the circuit are microprocessor-based. Feature allowing observing the received signals using oscilloscope is incorporated in the design. The design ensures output of current signal linearly dependent on the travetime of ultrasonic pulses from the radiator to the nearest baffler of the reflector under the fluid level and to the receiver. Processor performs the functions of strobing, computing and output signal normalization.

Experimental studies

Calibration of the instrument was performed at normal conditions by gradual submersion of the sensory element in water. Output current was measured in the process proportionally to the depth of sensory element submersion in the fluid. Standard deviation of the measured level from the trend line did not exceed 4 mm, which can be explained by the step of corrugations on the applied reflector equal to approximately 4.5 mm.

Experiments at elevated parameters were conducted in the water coolant at the saturation line within the pressure range from 0.1 MPa to 8 MPa. Experimental facility (Fig. 4) represents solid hermetically sealed pipe equipped with electrical heating inside which the level gage is mounted. Pipe made of stainless steel with 700-mm length and internal diameter equal to 35 mm was used. Heating element in the form of spiral made of nichrome with porcelain insulators is coiled over the pipe and is protected from the outside with thermal insulation on the basis of basalt continuous fiber. Water temperature and pressure inside the pipe are controlled. Heater power is controlled using laboratory autotransformer. Maximum coolant temperature can reach 357 °C.

Amplitude of received signal on which reliability of operation of the instrument depends to a significant extent is linearly dependent on the characteristic impedance of water. Dependence of characteristic impedance of water on the pressure value on the saturation line within the measured pressure range is presented in Fig. 5. Let us note that characteristic impedance within the pressure range in question decreases by approximately five times.

Boiling and partial evaporation of water takes place in the process of heating inside the hermetically sealed experimental section and increasing pressure suppresses development of boiling. Thus, isochoric thermodynamic process (at constant volume) is observed at the water saturation line. Here, with increased temperature and pressure water level gradually rises. Predicted calculation dependence of variation of water level on the pressure at the saturation line presented in Fig. 6 was determined (pressure is unequivocally dependent on the saturation temperature).

Calculations were perfromed according to the following formula:

$$h = m/(\pi r^2 \rho'), \tag{1}$$

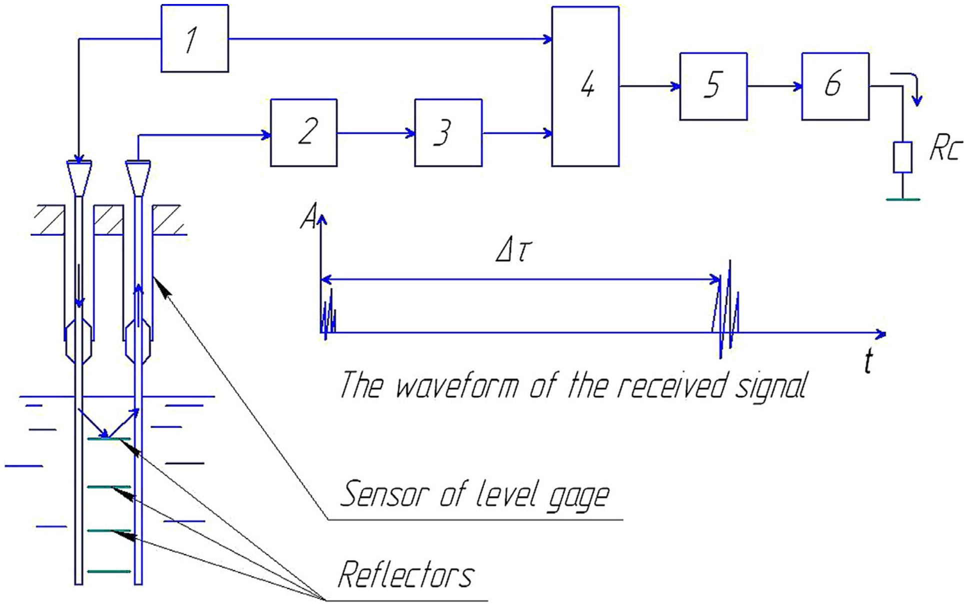

Fig. 3. Design of the electronics unit of the reflex-radar level gage: 1 – generator of video pulses; 2 – amplifier; 3 – comparator; 4 – time interval meter; 5 – digital-to analog converter; 6 – current generator.

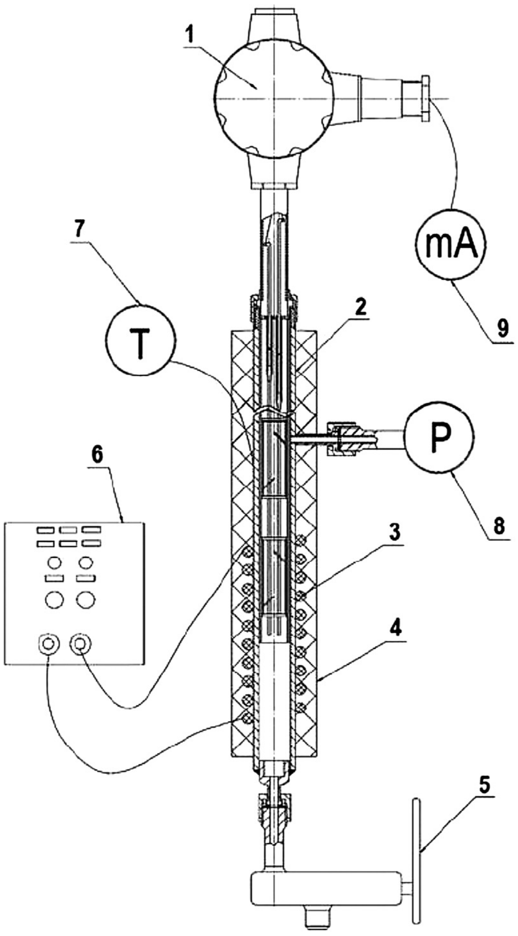

Fig. 4. Experimental installation: 1 – electronics unit; 2 – pipe; 3 – heating element; 4 – thermal insulation; 5 – drain valve; 6 – autotransformer; 7 - temperature measurement unit; 8 – pressure gauge; 9 – current meter.

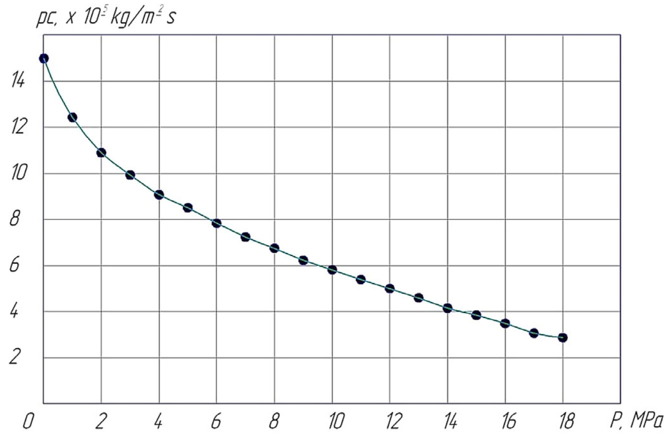

Fig. 5. Dependence of characteristic impedance of water on the pressure value on the saturation line.

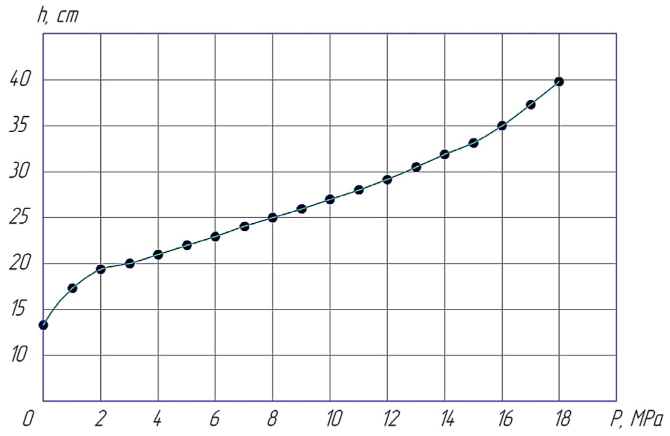

Fig. 6. Calculated dependence of variation of water level on the water saturation pressure line.

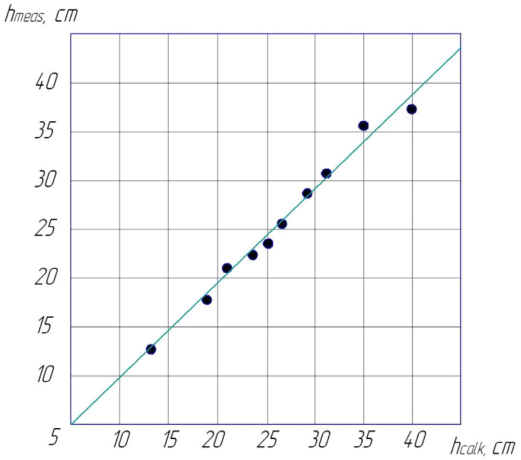

Fig. 7. Dependence of measured water level on the calculated level on the saturation line.

where h is the physical level of water in the pipe in the experimental section; m is the water mass in the pipe in the experimental section; r is the pipe internal radius; ρ' is the water density corresponding to the saturation line.

Prior to the implementation of the experiment the system is filled with water to the 450-mm mark from the pipe lower butt end, after that, level gage is installed (sensory element is submerged in the fluid to the depth of 130 mm) and sealing of the system is performed. After preparation of the measurement circuit electric power is supplied to the electrical heater with power equal to ~400 W. Temperature in the system is gradually increased at the rate of 7 °C/min to reach the value equal to ~350 °C. Pressure increases in the process to approximately 18 MPa. Coolant temperature and pressure inside the pipe are controlled, as well as acoustic signals and output current of the level gage.

Discussion of results

Dependence between the measured coolant level and the calculated level on the saturation line (Fig. 7) was determined in the course of experiments.

The obtained discrepancy between the coolant level measured using reflex-radar level gage and the factual value of the level is within the limits of ± 10 mm, i.e. agreement between the values is satisfactory enough. In such case within the whole measurement range of coolant parameters both in the primary and in the secondary cooling loops there will be no need to introduce corrections in the level gage readings.

Let us note that fluctuations of received acoustic signal were observed in the process of experiments, which is explained, in our opinion, by the boiling of the medium. In order to check the above assumption temporary switching off of the heater was undertaken resulting in the disappearance of fluctuations of received signals.

The most pronounced fluctuations of the signal are observed at pressure values in excess of 14 MPa. At the same time the algorithm selected by us allowed to a significant extent to remove the effects of fluctuations on the instrument output signal. Use of mathematical statistics methods for localization of maximum amplitude of receiver signal within the time interval under control allowing determining the most probable traveltime of ultrasonic signals along the travel path of the instrument is the distinguishing feature of the above algorithm.

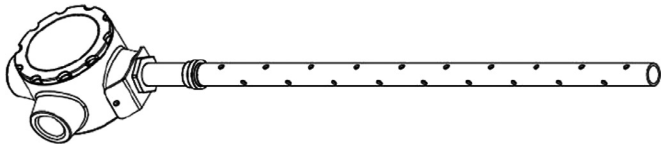

Fig. 8. External appearance of reflex-radar level gage with integrated electronics unit.

Conclusions

Originally developed design of ultrasonic level gage based on the reflex-radar measurement principle and suitable for application in equipment of power generation equipment was presented. The fact that time characteristic, namely, the travel time of ultrasonic pulses along the waveguide from the radiator along the line separating water and steam and back along the second waveguide to the receiver is the distinguishing feature of the measurement instrument. Let us note that measurement of time intervals is performed in a more straightforward way and, what is more important, more reliably as compared to the measurement of amplitudes of signals. Here, evolution of coolant parameters within wide range does not produce significant influence on the operation of the measurement instrument.

The fact that radiator and the receiver of the instrument are removed from the area under effects of high temperature and pressure and are connected with the medium under control by metal waveguides which significantly increases the instrument's lifespan and reduces its cost constitutes important feature of the level gage.

The level gage under discussion here is manufactured as the ready product, sketch drawing of which is presented in Fig. 8.

References

[1] V.I. Mel'nikov, V.P. Drobkov, V.V. Kontelev, Akusticheskie Metody Diagnostiki Gazozhidkostnykh Potokov (Acoustic Method Of Diagnostics of Gas-Fluid Flows), Energoatomizdat Publishers, Moscow, 2006, p. 351. (in Russian).

[2] V.I. Mel'nikov, Datchiki Sist. (Sens. Syst. J.) (n.12) (2011) 6–10 (in Russian).

[3] V.I. Melnikov, V.V. Ivanov, I.A. Teplyashin, Yu.A. Kiselev, A.N. Sninitsyn, A.V. Belin, Datchiki Sist. (Sens. Syst. J.) (n.11) (2013) 11–17 (in Russian).

[4] Dyudin B.V., Lependin L.F., Pavlyuk V.P., Plutenko A.D., Firsov N.P. Ultrazvukovoy Urovnemer Dlya Zhidkostu (Ultrasonic Level Gage for Liquid). Author's Certificate RF No. 322638. Published on 30.11. 1971, Bulletin No. 14 (in Russian).

[5] Dyudin B.V. Datchik Ultrazvukovogo Impulsnogo Urovnemera (Sensory Element of Ultrasonic Level Gage). Author's Certificate RF No. 510648. Published on 15.04. 1976, Bulletin No. 14 (in Russian).