Application of the Correlation Velocity Measurements for Hydrodynamic Investigations of Turbulent Coolant Flow in Nuclear Reactor Elements

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Abstract

The method of correlation measurement of the coolant flow rate, widely used for operational diagnostics of nuclear power plants, can be extensively used in research practice. The aim of this work was to apply a correlation method based on the conductometric measurement system with wire-mesh sensors for measuring a coolant flow rate.

Insignificant concentration of a salt solution (NaCl or Na_2SO_4) creates a gradient of the conductivity in the flow, which is used as a passive scalar measured by the system. Authors used turbulent pulsations at the interface of two concurrent flows with identical velocities in a square channel as a signal source for the correlation method. The paper presents the methodology of the tests, test facility description, signal-to-noise ratio estimation, the results of digital signal processing and comparison of the measured velocities in the model with the flowrate–averaged velocity determined by the use of flowmeters. The measured velocity values give acceptable agreement for the turbulent flow modes. It was shown that the measurement accuracy drops sharply for low-Reynolds flows.

The obtained results were used for flowrate measurements in core-imitator channels of the nuclear reactor test model.

The presented paper is an approbation of this approach for its application as part of an test model of a nuclear reactor in order to determine the each duct flow rates in the channels of the core simulator using wire mesh sensors.

Keywords: measuring system, correlation flowmeter, spatial conductometry, modeling of processes in the elements of nuclear power units.

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УДК 621.039

Применение корреляционного метода определения скорости потока теплоносителя при исследованиях гидродинамики турбулентных потоков в элементах ядерных реакторов

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Корреляционный метод измерения расхода теплоносителя, широко применяемый для эксплуатационной диагностики ядерных энергетических установок, может находить широкое применение в том числе и в исследовательской практике. Целью данной работы являлась отработка корреляционного метода измерения расхода теплоносителя с применением кондуктометрических систем.

В работе представлен вариант применения корреляционного метода для исследования турбулентных потоков на основе кондуктометрической измерительной системы – пространственных кондуктометров сетчатой конструкции. В качестве пассивной примеси используется незначительная концентрация раствора соли (NaCl или Na_2SO_4), создающей градиент проводимости среды, регистрируемый кондуктометрической системой. В качестве переносимых возмущений в работе используются турбулентные пульсации на границе раздела двух спутных струй с одинаковыми скоростями в канале квадратного сечения. Представлена методика проведения исследований на лабораторном стенде, результаты оценки отношения сигнал–шум измерительной системы, проведена обработка сигналов пространственных датчиков и сравнение измеренной скорости в модели со среднерасходной скоростью, определяемой с помощью показаний расходомеров стенда.

Результаты измерений дают приемлемое согласие с показаниями штатных расходомеров для характерных турбулентных режимов течения (погрешность измерения скорости потока при помощи кондуктометров составляет менее 5 %). Показано, что точность измерений резко падает для потоков с низким числом Рейнольдса.

Представленная работа является апробацией данного подхода для его применения в составе экспериментальной модели ядерного реактора с целью определения поканальных расходов в каналах имитатора активной зоны при помощи сетчатых кондуктометрических датчиков.

Ключевые слова: измерительная система, корреляционный расходомер, пространственная кондуктометрия, моделирование процессов в элементах ЯЭУ.

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Introduction

In the modern designs of nuclear power plants a special attention is paid to improve the reliability, safety and economy of the operation. These requirements dictate the need for experimental studies on large-scale models of elements of nuclear power plants [1], which in turn raises the question of the development of new control systems for the most important parameters of the reactor plant (RP) which include the flow rate of the coolant in various elements of nuclear power plants.

Currently known is the correlation method for measuring the flow rate of the coolant, the main requirement of which is the presence of some passive scalar flow function, convectively transferred along with the current mass. It allows one to implement correlation measurements using various methods for measuring flow properties: temperature, content of radioactive isotopes, optically distinguishable impurities, etc. [2].

In nuclear power, the correlation method is used to determine the flow rates in the loops of a reactor plant. It is based on the analysis of the readings of detectors of gamma radiation caused by the activation of the O^{16} isotope in the neutron field of the core [3]. In the Russian nuclear power industry, this method was first applied to measure the flow rate of the primary circuit of a channel reactor [4]. Later in the prototype of the system for correlation control of the coolant flow rate of the pressure vessel reactor installed reactor at the Kalinin nuclear power plant [5], [6].

However, this method cannot be applied for laboratory studies of the reactor thermohydraulics, since there are no necessary radionuclides in the simulated flow. This problem can be solved by a measuring system based on the conductometric sensors widely used in research practice with a hydrodynamically passive admixture protruding as a tracer.

The purpose of this work was to develop a correlation method for measuring the flow rate of a heating agent using conductometric systems.

Test facility

The general circuit of the TF (Figure 1) allows to perform experiments with isothermal mixing in an open circulation loop (with the use of flows with different concentrations of impurities) and non-isothermal mixing when using flows with different temperatures.

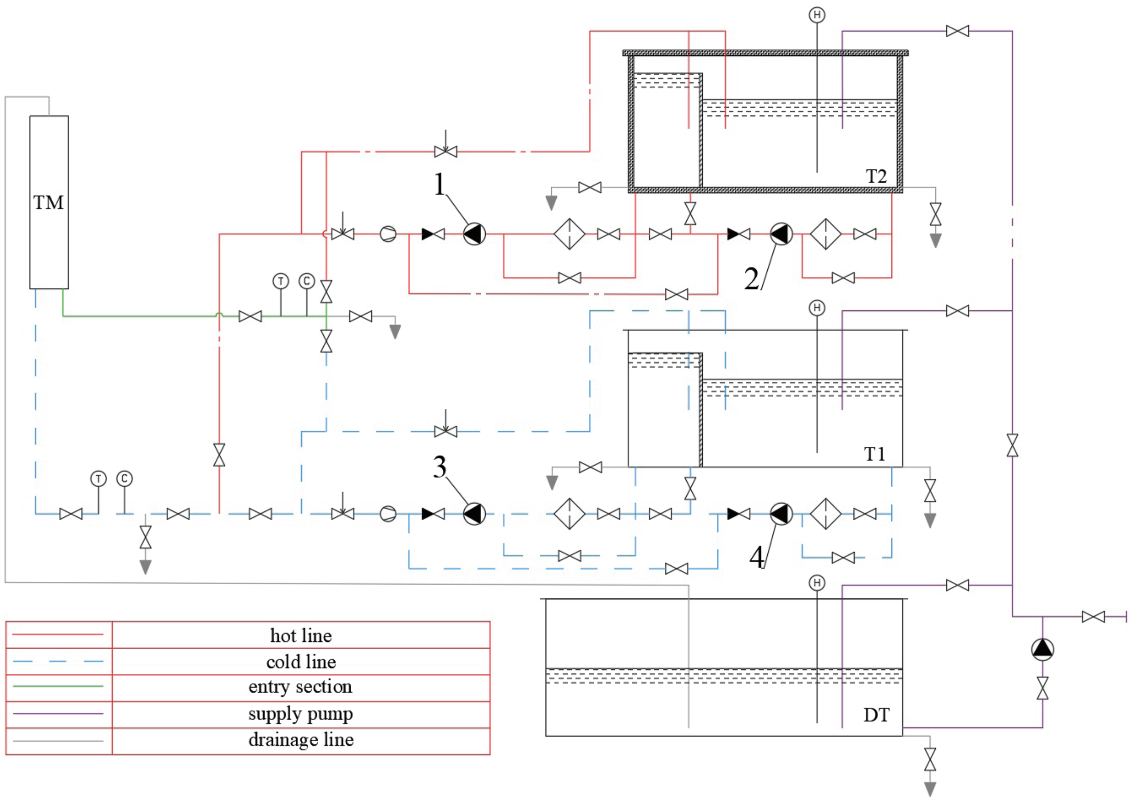

Figure 1 – Hydraulic diagram of the test facility: 1 – hot linecirculation pump; 2 – hot line supply pump; 3 – cold line circulation pump; 4 – cold line supply pump; T1 – cold tank; T2 – hot tank; DT – drainage tank; TM – test model

The mixed streams are supplied by the boost pumps (2 and 4) to the constant level tank volumes, from which they are fed to the suction side of the circulation pumps (1 and 3). This solution provides a constant hydrostatic pressure at the suction of the pumps, which is one of the main criteria to maintain the stationary mixing process. Further, the streams are pumped along the supply lines through the test model and enter the drainage tank. The valves of the supply line assumes the possibility of the fluid from each tank to enter the upper or lower branch pipes of the model, or to direct a fluid from one of the tanks to both branch pipes.

The equipment of the TF makes it possible to create both laminar and turbulent flow mode (with Re from 900 to $12 \cdot 10^3$) at different temperatures, flow rates and concentration of impurities in the coolant flow. The main characteristics of the TF are shown in Table 1.

Table 1

Main parameters of the test facility

Parameter	Value
The total power of the heaters, kW	12
Flow through test model, m^3/hr	up to 2.9
Temperature of the mixing flows, °C	10–60

The measuring system of the TF consists of a technological part, which is necessary to control the mode parameters of the installation, and the research part, which is necessary for measuring the physical characteristics in the zone of turbulent flow mixing [7].

The measurements were carried out by method of conductometry using two wire mesh sensors (WMS) with location of cells 8×8 and a step between the centers of adjacent cells of 5 mm [8].

The output current of the measuring system is proportional to the electrical conductivity, which depends on the salt content in the measuring cells of the WMS. Before the measurements, the WMS cells were calibrated to eliminate common and systematic errors in measuring electrical conductivity.

Measuring principle

The measurements were carried out in a test model with a square cross section of 50×50 mm, the general view of which is shown in Figure 2. The WMSs were installed in a zone of intensive mixing at axial distance of 500 mm.

The mass flow rate measurements were performed in the range from 0.173 m^3/h (Re = 900) to 2.64 m^3/h (Re = $12 \cdot 10^3$). The actual flow rate was recorded using individually calibrated flow meters [4].

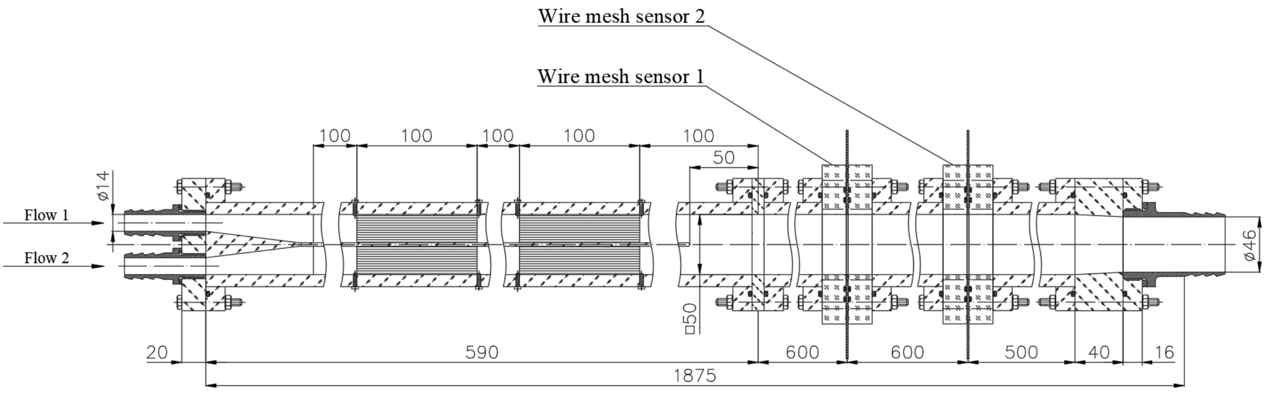

Figure 2 – Test model

The basis of the used flow measurement method is to determine the time of transport of the turbulent fluctuations between two WMS. For this purpose, an algorithm of cross-correlation (CCF) between the electric conductivities $X(t)$ and $Y(t)$, determined by the WMS was used. The discrete CCF of time sequences $X(t)$ and $Y(t)$ was calculated as follows:

$$R_k(X,Y) = \frac{1}{\sqrt{R_{xx}(0)\,R_{yy}(0)}} \cdot \frac{1}{N} \sum_{t=0}^{N-k-1} x_t \cdot y_{t+k}, \quad (1)$$

where: $\frac{1}{\sqrt{R_{xx}(0)\,R_{yy}(0)}}$ – CCF normalization parameter; x_t – electrical conductivity obtained from the first WMS; y_{t+k} – electrical conductivity obtained from the second WMS $(t+k)$; k – shift by time axis; N – number of counting in implementation; $k = 0, 1, ..., N - 1$ – sample numbers.

Because of the measurements were carried out using WMS, after applying the specified algorithm, an array of velocities in the measuring cells of the WMS was obtained. The cell numbering is shown in Figure 3.

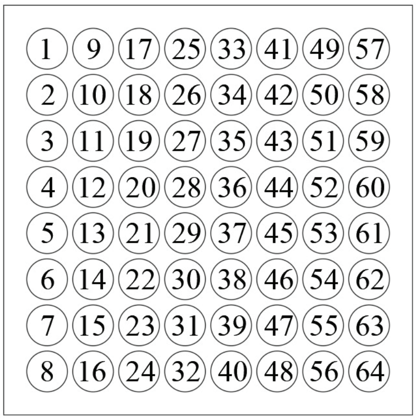

Figure 3 – Measuring cells of WMS

The obtained velocity values depend on the position of the measuring cells in the channel section. This happened because the intensity of the turbulent pulsations in the center of the channel is greater than at the periphery, as a result of which the cross-correlation between the readings of electrical conductivity between the central cells of the sensors is much stronger than between the peripheral ones. By this reason, the assessment of the integral characteristic of the velocity over the channel section of the test model was carried out using weight coefficients:

$$\bar{w} = \frac{\sum \omega_i \cdot w_i}{\sum \omega_i}, \quad (2)$$

where: i – WMS cell number; ω_i – weight coefficient of i-th cell; w_i – flow rate in the i-th measuring cell.

In this case, the contribution of a particular cell to the integral estimate of the velocity will be proportional to the variance and the correlation coefficient between the readings of the electrical conductivity of the first and second WMSs in the i-th measuring cell. Based on this, the weight coefficients for each cell were calculated as follows:

$$\omega_i = \left(\sigma^2{}_i\right)^2 \cdot \rho_i, \quad (3)$$

where: σ_i^2 – variance of readings in the i-th measuring cell; $\rho_i = \max(|R_k(X, Y)|)$ – correlation coefficient between the readings in the i-th measuring cell of the first and second WMS.

Measurement results

As a result of the measurements, instantaneous and averaged values of electrical conductivity at the cells of the sensors were obtained. Figure 4 shows an example of the measured conductivity in test with $\mathrm{Re} = 12 \cdot 10^3$.

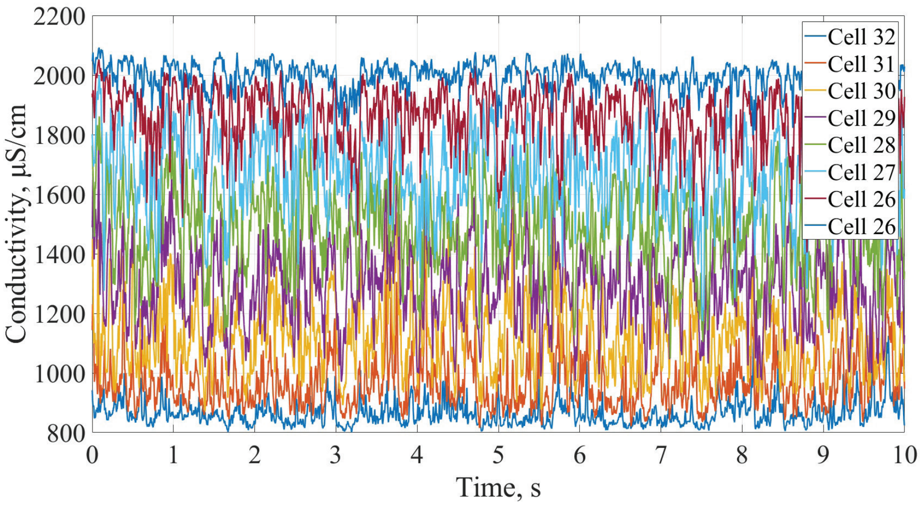

Figure 4 – Example of the electrical conductivity data in test with $\mathrm{Re} = 12 \cdot 10^3$

Figure 5 shows the distribution of the averaged electrical conductivity over the measuring cells for the data in test $\mathrm{Re} = 12 \cdot 10^3$ and $\mathrm{Re} = 900$.

The presence of a sharp leap in the conductivity for $\mathrm{Re} = 900$ indicates the absence of mixing of flows in this test. Conversely, the smooth distribution of conductivity over the cells with a simultaneous shift of the maximum readings to the center indicates a significant intensity of turbulent pulsations in the test with $\mathrm{Re} = 12 \cdot 10^3$.

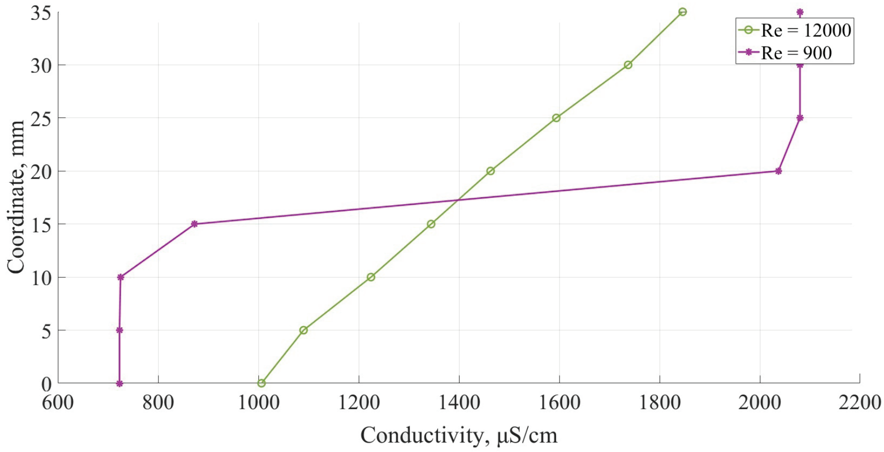

Figure 5 – Averaged electrical conductivity in measuring cells in tests with Re = $12 \cdot 10^3$ and Re = 900

The first objective was to assess the effect of noise on the measurement results. To obtain this estimate the electrical conductivity in a flow without a tracer was measured. Further, based on the analysis of the power spectral density (PSD) and the estimation of the main vortex frequencies noise intensity and it's frequency band were obtained. In this case, the assessment noise frequency band was f_{noise} = 61 Hz. The resulting periodograms are shown in Figure 6.

Further correlation measurements were carried out using a digital low-pass filter with a passband f_{stop} = 40 Hz.

Figure 7 shows a view of the wire mesh sensor realization after passing through a low-pass filter. The signal shape for the central cells shows a high level of their correlation.

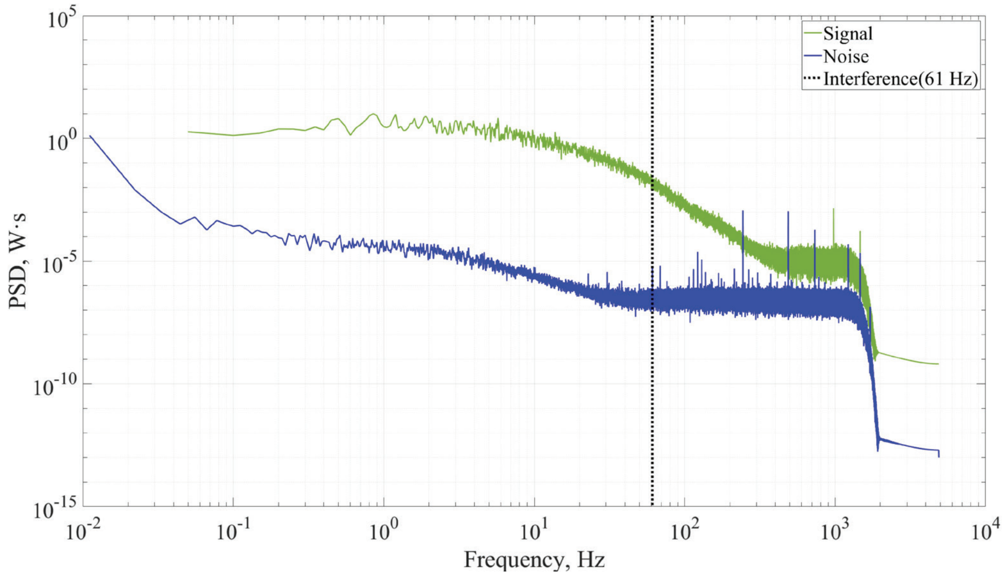

Figure 6 – Periodograms of power spectrum density (PSD) during "contrast mixing" (signal) and "non-contrast" mixing (noise)

A high level of correlation for the central cells (ρ = 0.63) provides good accuracy in determining the time shift (τ = 4.78 c).

Table 2 shows the data on the flow rate obtained by the correlation method in comparison with the readings from the flow meters of the TF.

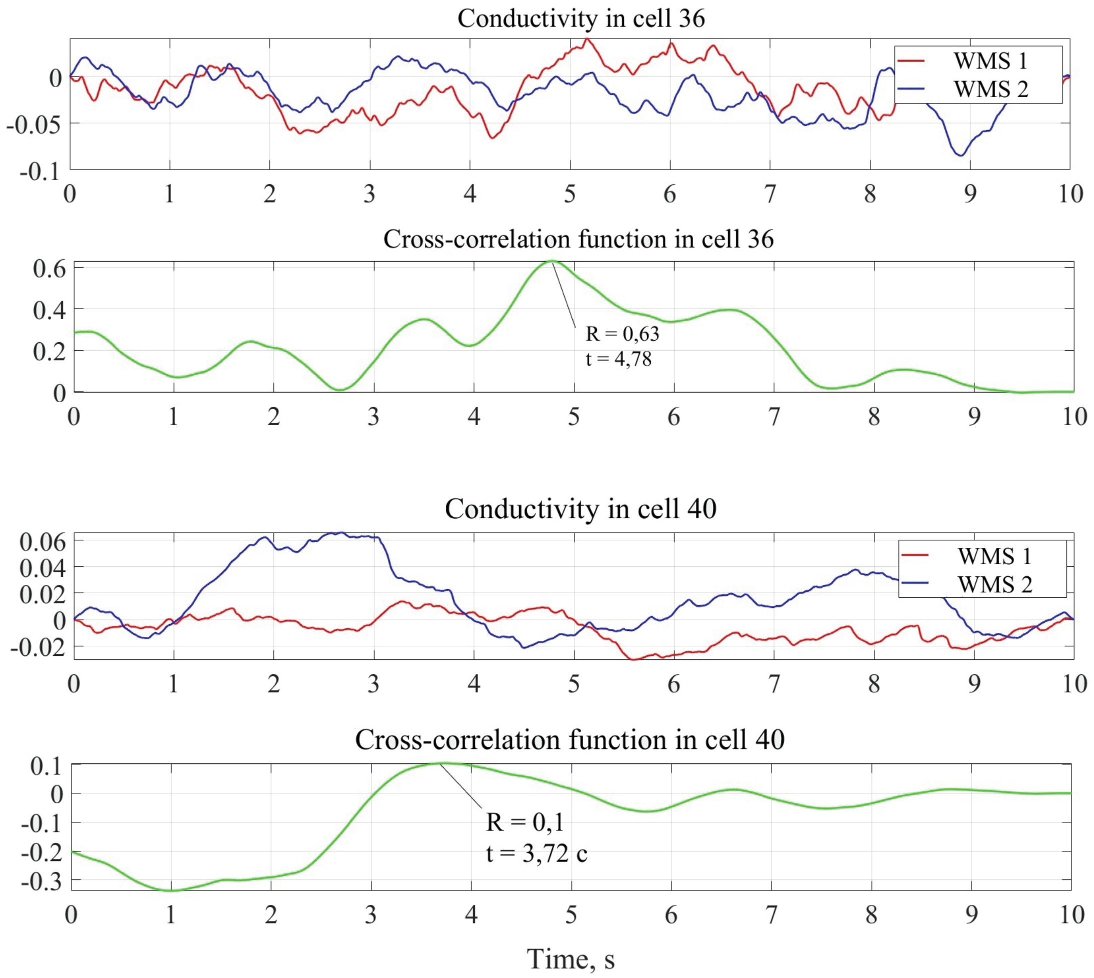

Figure 7 – Electrical conductivities and cross-correlation functions in test with $\mathrm{Re} = 6.3 \cdot 10^3$ for central and peripheral cells

Table 2

Comparative analysis of values

Parameter	Reynolds		
	Re = 900	Re = 6300	Re = 12000
Flow according to standard flowmeters, l/min	2.88	22.38	43.92
Correlation flow, l/min	110.25	23.25	44.7
Relative error	3719 %	4 %	2 %
Correlation velocity, m/s	0.735	0.155	0.298
Temperature, °C	27.4	27.4	27.4
Density, kg/m^3	996.41	996.41	996.41

The readings obtained indicate the presence of an error of less than 5 % for higher Re numbers, while with decreasing Re, an increase of the error is observed. This is explained by the significant (in comparison with the size of the energy-carrying vortices) distance between the WMS. The intensity of turbulence in the mixing zone decreases with the decrease of Re number, which causes the decrease of correlation strength between the readings of the sensors. In this case, for Re = 900, there is no correlation between the readings of the sensors due to the homogeneity of the flow in the laminar mode.

Conclusion

The approbation of the method of correlation determination of the coolant flow carried out in this work on the basis of a conductometric measuring system for turbulent flow in a square channel made it possible to apply this method to measure channel flow rates in scale models of elements and equipment of the core of a nuclear power plant.

The discharge results obtained for various Reynolds flows indicate a strong dependence of the flow rate measurement accuracy on the turbulence intensity. Furthermore, measurement results for Re = 900 allow making a general conclusion about the presence of a lower limit of the measured flow rate which will depend on temperature, flow rate and distance between sensors. Hence this limit will be different for each specific event.

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