Development and Testing of a Methodology for Assessing of the Correlation Velocity Measurements' Accuracy for the Hydrodynamic Investigations of the Turbulent Coolant Flow in Nuclear Reactor Elements

I.A. Konovalov, A.A. Chesnokov, A.A. Barinov, S.M. Dmitriev, A.E. Khrobostov, M.A. Legchanov, S.S. Borodin, M.A. Makarov

Nizhny Novgorod State Technical Univercity n.a. R.E. Alekseev,
Minin str., 24, Nizhny Novgorod 603950, Russia

Abstract

The correlation method of the coolant flow measuring is widely used in research practice including for studying of turbulent coolant flows in scale models of elements of nuclear power plants. The aim of this work was to develop a technique for assessing the effect of noise recorded by a measuring system on the flow rate readings obtained using the correlation method.

A technique to assess the effect of noise as well as the relative position and acquisition period of sensors is presented. An insignificant concentration of a salt solution (NaCl or Na_2SO_4) is used as a passive impurity which creates a conductivity gradient of the medium recorded by a conductometric system. Turbulent pulsations at the interface between two concurrent isokinetic flows in a channel with a square cross section are used as the signal source for the correlational algorithm.

Paper presents the values of the turbulence′s transport time between spatial conductometers, the results of estimating the spectral power density and band of the recorded signal and also the signal-to-noise ratios of the measuring system obtained on their basis which are subsequently used to estimate the confidence interval of the transport time.

As a result of measurements the relationship between the confidence interval value and the signal length were obtained. The measurements which were carried out at different relative positions of conductometers make it possible to make a conclusion about an increase in the spectral width of the signal and, as a consequence, a decrease in the length of the confidence interval with increasing of distance between sensors.

The presented work is an approbation of this approach for its application as part of an experimental model of a nuclear reactor in order to determine per-channel flow rates in the channels of the core simulator using mesh conductometric sensors taking into account the effect of noise.

Keywords: spatial conductometry, wire mesh sensor, modeling of processes in the elements of nuclear power units.

Адрес для переписки: *Коновалов И.А.* *Нижегородский государственный технический университет,* *ул. Минина, 24, г. Нижний Новгород 603950, Россия* *e-mail: iliakonowaloff@yandex.ru*	*Address for correspondence:* *Konovalov I.A.* *Nizhny Novgorod State Technical Univercity,* *Minin str., 24, Nizhny Novgorod 603950, Russia* *e-mail: iliakonowaloff@yandex.ru*
Для цитирования: *I.A. Konovalov, A.A. Chesnokov, A.A. Barinov, S.M. Dmitriev,* *A.E. Khrobostov, M.A. Legchanov, S.S. Borodin, M.A. Makarov.* Development and Testing of a Methodology for Assessing of the Correlation Velocity Measurements' Accuracy for the Hydrodynamic Investigations of the Turbulent Coolant Flow in Nuclear Reactor Elements. Приборы и методы измерений. 2021. – Т. 12, № 1. – С. 67–74. **DOI:** 10.21122/2220-9506-2021-12-1-67-74	*For citation:* I.A. Konovalov, A.A. Chesnokov, A.A. Barinov, S.M. Dmitriev, A.E. Khrobostov, M.A. Legchanov, S.S. Borodin, M.A. Makarov. Development and Testing of a Methodology for Assessing of the Correlation Velocity Measurements' Accuracy for the Hydrodynamic Investigations of the Turbulent Coolant Flow in Nuclear Reactor Elements. *Devices and Methods of Measurements.* 2021, vol. 12, no. 1, pp. 67–74. **DOI:** 10.21122/2220-9506-2021-12-1-67-74

Разработка и апробация методики оценки точности корреляционного определения скорости потока теплоносителя при исследованиях гидродинамики турбулентных потоков в элементах ядерных реакторов

И.А. Коновалов, А.А. Чесноков, А.А. Баринов, С.М. Дмитриев, А.Е. Хробостов, М.А. Легчанов, С.С. Бородин, М.А. Макаров

Нижегородский государственный технический университет имени Р.Е. Алексеева,
ул. Минина, 24, г. Нижний Новгород 603950, Россия

Корреляционный метод измерения расхода теплоносителя находит широкое применение в исследовательской практике, в том числе для изучения турбулентных потоков теплоносителя в масштабных моделях элементов ядерных энергетических установок. Целью данной работы являлась отработка методики оценки влияния шума, регистрируемого измерительной системой, на показания скорости потока, полученные с применением корреляционного метода.

Представлена методика оценки влияния шума, а также взаимного расположения и периода опроса чувствительных элементов на основе кондуктометрической измерительной системы: пространственных кондуктометров сетчатой конструкции. Незначительная концентрация раствора соли (NaCl или Na_2SO_4) используется в качестве пассивной примеси, 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.

Представлены значения времени транспорта турбулентности между пространственными кондуктометрами, результаты оценки спектральной плотности мощности и ширины регистрируемого сигнала, а также полученные на их основе отношения сигнал-шум измерительной системы, в дальнейшем использованные для оценки доверительного интервала времени транспорта.

В результате измерений получены зависимости величины доверительного интервала от времени регистрации показаний пространственных кондуктометров. Измерения, проведённые при различном взаимном расположении кондуктометров, позволяют сделать обобщающий вывод о росте спектральной ширины сигнала и, как следствие этого, уменьшение длины доверительного интервала с увеличением расстояния между датчиками.

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 с учётом влияния шума, регистрируемого измерительной системой.

Ключевые слова: пространственная кондуктометрия, сетчатый датчик, кондуктометрический датчик, моделирование процессов в ЯЭУ.

Приборы и методы измерений
2021. – Т. 12, № 1. – С. 67–74
I.A. Konovalov et al.

Devices and Methods of Measurements
2021, vol. 12, no. 1, pp. 67–74
I.A. Konovalov et al.

Introduction

Nowadays special attention is paid to experimental studies of the hydrodynamic characteristics of the coolant flow in scale models of elements of nuclear power plants which are aimed at validating the computational models necessary to substantiate the reliability and safety of structures [1]. The question about the control of the indicators of the coolant flow rate in the elements under study when carrying out such experiments is often arised.

At the moment the correlation method for measuring the flow rate of a coolant is widely known the main requirement of which is the presence of a certain passive scalar flow function convectively transferred along with the flowing medium. It allows one to implement correlation measurements using various methods for measuring the properties of the flow: temperature, content of radioactive isotopes, optically distinguishable impurities, etc. [2–3]. This approach assumes determination of the transit time of the disturbance of the measured quantity (the so-called turbulence transport time) between the sensitive elements of the system which are located at some distance from each other.

The paper [4] presents a method of using a conductometric measuring system for the correlation determination of the flow velocity [5–7] based on the determination of the cross-correlation function maximum as the time of turbulence transport between sensors. To improve the measurement accuracy and reduce the influence of the most intense pickups a digital low-pass filter was used in the specified work [4] when processing the measuring signal [8]. However the question about assessing the contribution of the "noise" passed by the low-pass filter to the relative error in determining the position of the cross-correlation function maximum remains open.

This problem directly affects the measuring accuracy of the coolant flow rate in the elements of nuclear power plants therefore in the case of research facilities it can have a significant impact on results of experimental data processing which are used to substantiate the reliability and safety of the structures under study.

In correlation measurements of the flow velocity the duration of the realization is very important according to which the cross-correlation function is calculated. Therefore the question about the methodology for choosing of the optimal sampling rate of measuring elements (in this case conductometric sensors) arises, which would satisfy the conditions for maintaining an acceptable measurement accuracy at the maximum sampling rate of readings.

From the above it follows that the purpose of this work was to determine the confidence interval when finding the turbulence transport time between the measuring elements and to estimate the dependence of the confidence interval length on the recording period of the flow rate readings.

Test facility

The general layout of the stand (Figure 1) assumes the organization of an experimental regime with isothermal mixing in an open circulation loop (for studies flows with different concentrations of impurities were used) and non-isothermal mixing when flows with different temperatures were used.

The equipment of the stand makes it possible to create both laminar and turbulent flow regimes (with Re up to $20 \cdot 10^3$) at different temperatures, flow rates and tracer concentrations in the coolant flow. The main parameters of the test facility are shown in Table 1.

Table 1

Parameters of the test facility

Parameter	Value
Total heaters power, kW	12
Flow through test model, m^3/hr	to 2.1
Temperature of the mixing flows, °C	10–60

Experiments

Measurements were carried out in a test model with a square cross section of 50×50 mm^2, the general view of which is shown in Figure 2. The model repeats in general details of the test model geometry from [9]. Wire mesh sensors (WMS) were installed in a zone of intense mixing at different distances from each other.

Measurements were carried out in the flow range up to 2.1 m^3/h (Re = $20 \cdot 10^3$).

The main parameters of the experimental modes are presented in Table 2.

For each mode "non-contrast measurements" were made in which there was no impurity tracer in the mixed flows creating a gradient of the medium conductivity. In this case reading signals′ fluctuations of the mesh sensors were determined only by the noises recorded by the measuring system. These measurements were used to estimate the noise level and to determine the signal-to-noise ratio.
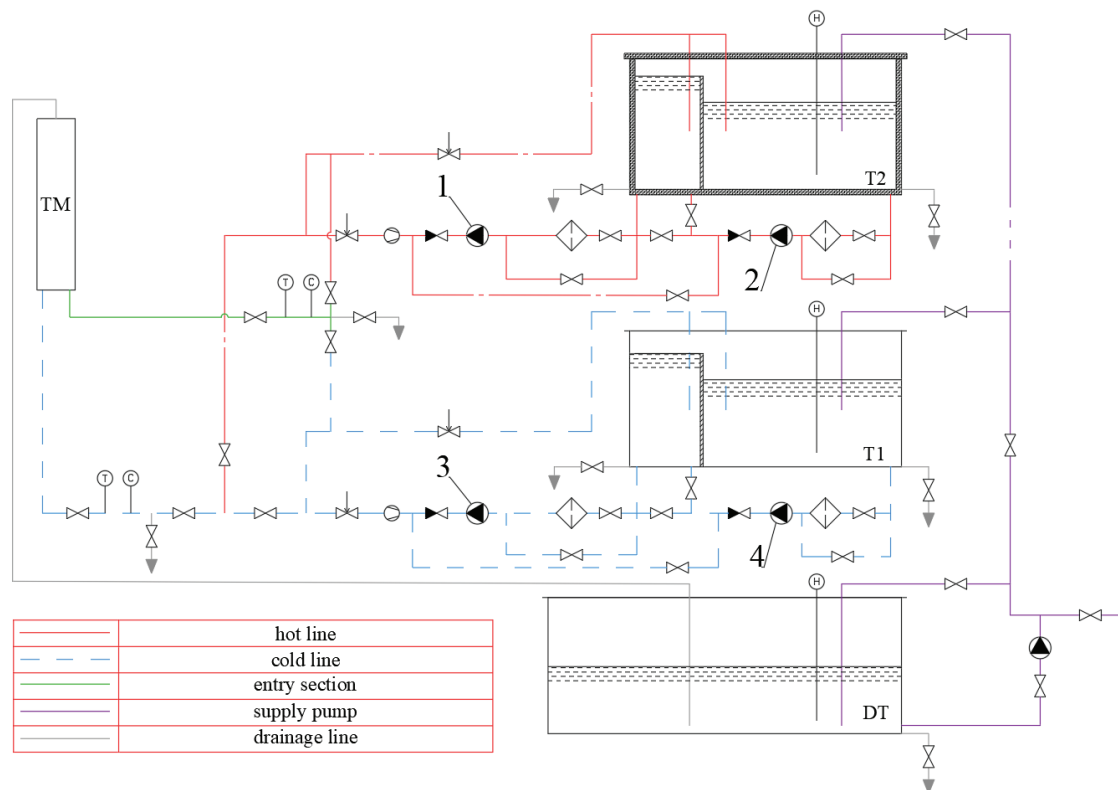
Приборы и методы измерений
2021. – Т. 12, № 1. – С. 67–74
I.A. Konovalov et al.

Devices and Methods of Measurements
2021, vol. 12, no. 1, pp. 67–74
I.A. Konovalov et al.

Figure 1 – Hydraulic diagram of the test facility: 1 – hot line circulation 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
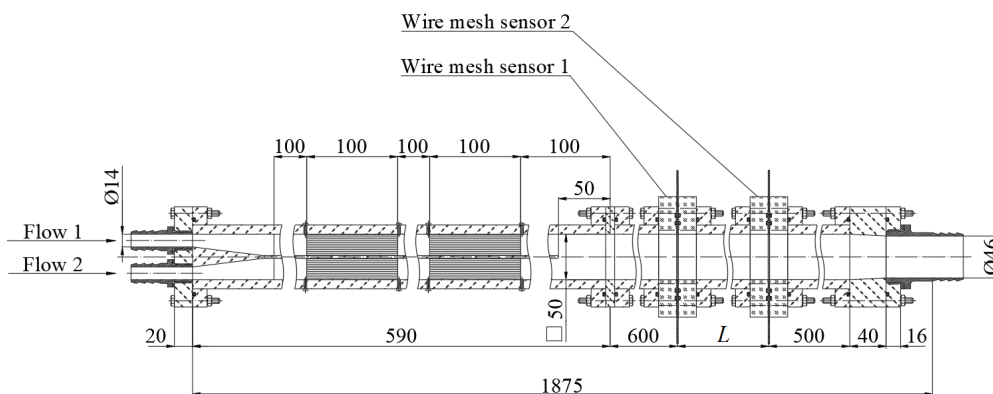

Figure 2 – Test model

Table 2

Main parameters of the experimental modes

Re·10³	Temperature of the mixing flows, °C	Conductivity of salty flow, µS/cm	Conductivity of bulk flow, µS/cm	Distance between wire mesh sensors, mm	Duration of realization, s
	45.0	1302.0	1030.0	640	120
	44.9	1335.0	1045.0	440	120
20	44.9	1311.0	1029.5	240	120
	44.7	1318.0	1029.0	40	120

Приборы и методы измерений
2021. – Т. 12, № 1. – С. 67–74
I.A. Konovalov et al.

Devices and Methods of Measurements
2021, vol. 12, no. 1, pp. 67–74
I.A. Konovalov et al.

Measurements of the coolant velocities in the cells of the wire mesh sensors were carried out in accordance with the procedure described in [4]. The accepted cell numbering is shown on Figure 3.
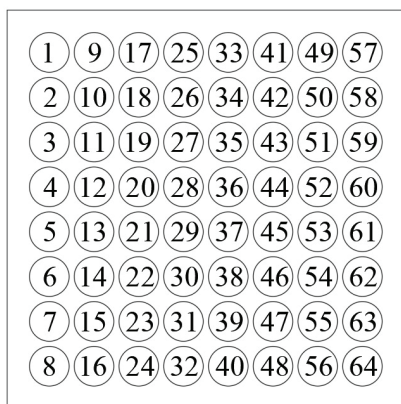

Figure 3 – Cells layout of wire mesh sensors

The experimental data are instantaneous and averaged conductivity fields, mode parameters, and averaged values of flow velocities in the model obtained by the correlation method.

Method of experimental data processing

In accordance with the method described in [10] estimation of the confidence interval for the turbulence transport time estimate between sensors is reduced to the determination of the normalized root-mean-square error of the cross-correlation function which for the frequency-limited "white noise" has the form [11]:

$$\varepsilon^2[R_{xy}(\tau)] = \frac{1}{2B \cdot T}(2 + (M/S) + (N/S) + (M/S)(N/S)), \quad (1)$$

where: $R_{xy}(\tau)$ – the value of the mutual correlation function at the moment of time τ; T – duration of realization, s; B – spectral width of white noise, Hz; M/S, N/S – the signal-to-noise ratio of the first and second WMS, respectively.

Assuming that the measurement signal $S(t)$ can be considered as frequency-limited "white noise" from expression (1) we obtain:

$$\varepsilon^2[R_{xy}(\tau)] = \frac{1}{2B \cdot T}(2 + (S/M) + (S/N) + (S/M)(S/N)). \quad (2)$$

In this case, the band of the measurement signal B can be defined as the frequency interval containing 95 % of the energy of the signal under investigation. The definition of B was made based on the analysis

of the energy spectrum of the conductivity pulsations in the mixing zone obtained by the method of the modified Welch's periodogram using the expression:

$$0.95 \cdot W = \int_0^B P(f) \cdot df, \quad (3)$$

where: W – the power carried by the signal in the entire considered frequency range, W; $P(f)$ – the function of the spectral power density, W·s; f – frequency of pulsations of electrical conductivity in the measuring area, Hz.

The signal-to-noise ratio (Figure 4) was estimated individually for each sensor as the average quotient of spectral densities of the noise and signal in the band range B:

$$S/M = \frac{1}{B} \cdot \int_0^B \frac{S(f)}{M(f)} \cdot df, \quad (4)$$

where: $S(f)$, $M(f)$ – the functions of the spectral power density for contrast (signal) and non-contrast (noise) mixing, respectively, W·s; f – frequency of pulsations of specific electrical conductivity in the measuring area, Hz.
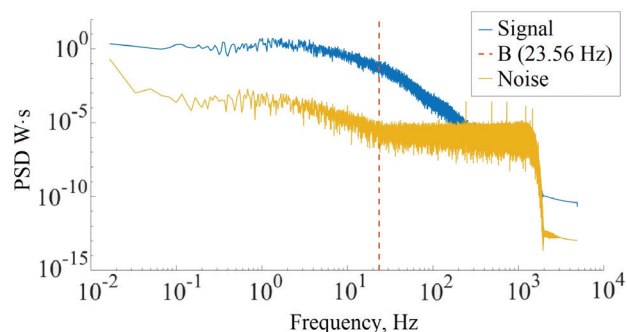

Figure 4 – Summary chart of power spectrum density (PSD) during "contrast mixing" (signal) and "non-contrast" mixing (noise) in cell 28 for experiment with Re = 20·10³ (distance between WMS 240 mm)

Finally, the 95 % confidence interval in determining of the position of the maximum of the cross-correlation function was determined based on the expression:

$$[-2 \cdot \sigma_i(\tau_{max}) \leq \tau_{max} \leq 2 \cdot \sigma_i(\tau_{max})], \quad (5)$$

where: τ_{max} – the time shift corresponding to the position of the maximum of the mutual correlation function (turbulence transport time), s; $\sigma_i(\tau_{max})$ – the variance of the normalized root-mean-square error, defined as:

$$\sigma_i(\tau_{max}) \approx (\varepsilon^2[R_{xy}(\tau_{max})])^{1/4}. \quad (6)$$

Приборы и методы измерений
2021. – Т. 12, № 1. – С. 67–74
I.A. Konovalov et al.

Devices and Methods of Measurements
2021, vol. 12, no. 1, pp. 67–74
I.A. Konovalov et al.

Analysis of results

As a result of processing the experimental data in accordance with the method described above, the cross-correlation functions of the realizations of the first and second WMS were obtained, the averaged values of the flow rates in the measu-ring cells of the sensors were obtained, and the confidence interval was evaluated when determi-ning the position of the maximum of the cross-correlation function. Figure 5 shows the graphs of the cross-correlation function with the designated confidence intervals for the mode Re = 20·10^3 at various distances between the sensors.
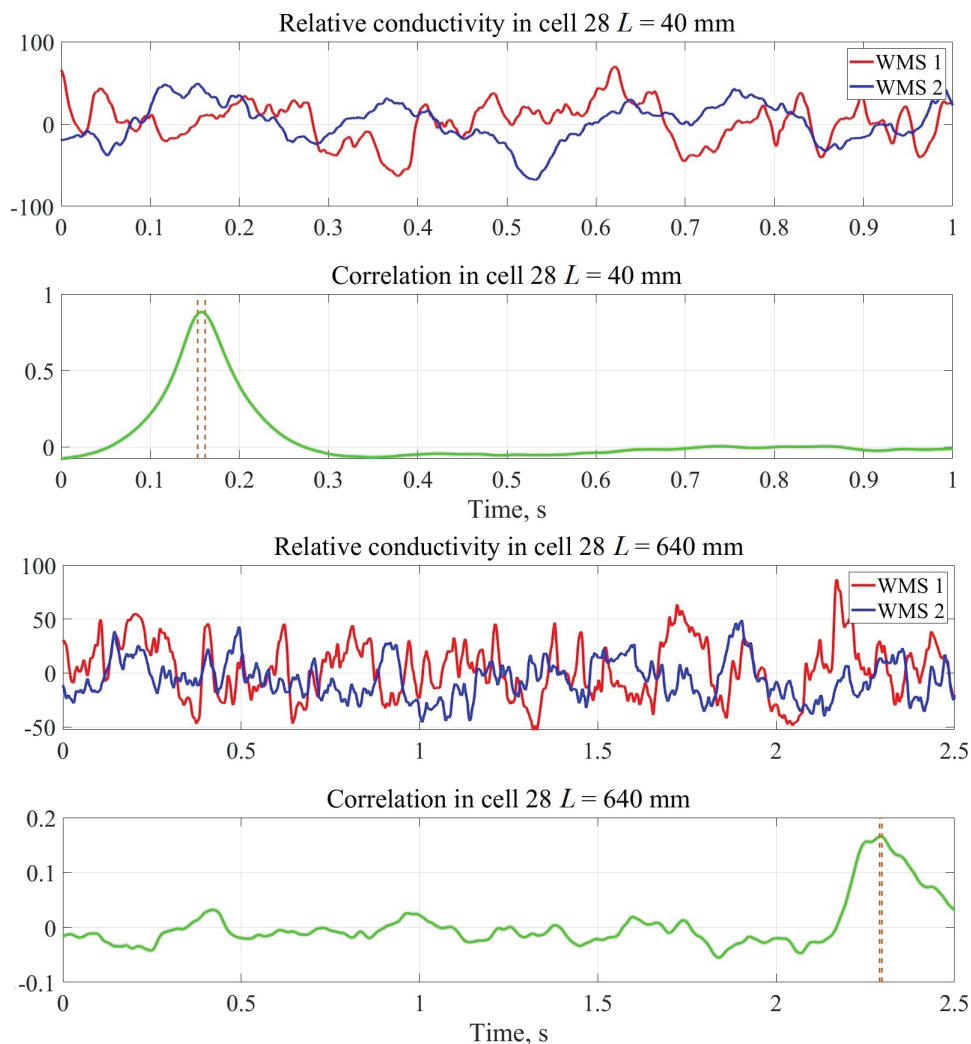

Figure 5 – Normalized electrical conductivities and cross-correlation functions in test with Re = 20·10^3 with different distances between wire mesh sensors for cell 28

Graphs show that with an increase of the dis-tance between the measuring planes of the wire mesh sensor from 40 mm to 640 mm (approximately equal to the scale of the main energy-carrying vortices) a significant decrease in the level of signal correlation is observed.

Numerical estimates of the deviations in determining the position of the function maximum were obtained, as well as the variance of the normalized mean square error of the maximum position. Also average values of the measuring signal band and data on the average flow rate were obtained. The results are recorded in Table 3.

Studies of dependence of the confidence interval length on the duration of realization were carried out on the basis of dividing the initial signal realization (duration 120 s) into windows with durations ranging from 1 to 120 s (120 and 1 window, respectively). Further, in accordance with the technique (1)–(6), the confidence interval of the cross-correlation function maximum position was estimated for each window.

The results of the experimental data processing for the mode with $Re = 20 \cdot 10^3$ at a distance between the WMS of 40 mm are shown in Figure 6 as the dependence of the absolute interval length on the interrogation period of the WMS.
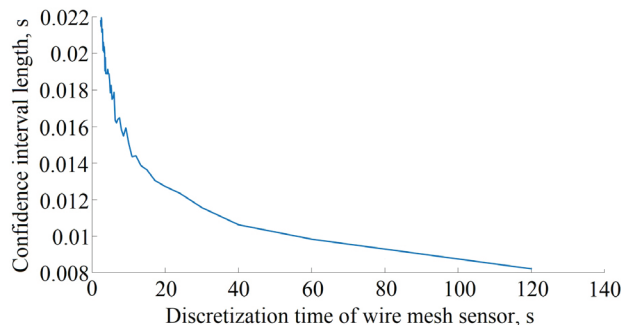

Figure 6 – Dependence of confidence interval on discretization time (time window) of wire mesh sensors

The graph shows the exponential dependence of the confidence interval length and consequently, the measurement accuracy on the duration of the realization (time window).

The dispersion of τ_{max} values was taken as a criterion for stability of determining of the cross-correlation function maximum position for each window within one realization (Figure 7).
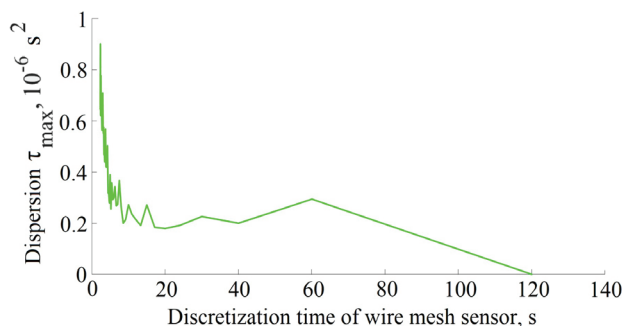

Figure 7 – Dispersions of turbulence transport time per discretization time (time window) of wire mesh sensors

The graph shows that the variance values do not exceed 10^{-6} s^2. This indicates that the readings of the first and second wire mesh sensors are correlated along all the considered window lengths.

Conclusion

The experimental data analysis made it possible to estimate the confidence interval of the cross-correlation function maximum position for the correlation method of measuring of the flow rate of the coolant turbulence transport time based on the

correlation methodlogy. The obtained value of the relative deviation in determining of the turbulence transport time between the measuring planes of the mesh sensors indicates a low contribution of the "noise" recorded by the conductometric measuring system to the signal under study.

A decrease in the distance between the sensors allows one to obtain a higher value of the correlation coefficient which, in turn, can affect the accuracy of determining of the position of the cross-correlation function maximum when measuring the flow velocity with a low degree of turbulence. However, this entails an increase in the relative error in the study of high-speed flows due to decrease in the total time of turbulence transport between mesh conductometric sensors.

The results of the work can be used to determine the optimal relative position and interrogation period of sensors designed to register changes in time of a certain scalar quantity (temperature, concentration, radioactivity, etc.) when using sensors to determine the flow rate by the correlation method of measuring the speed for correlation flow rate methodology.

Acknowledgments

References

1. Rohde U., Kliem S., Hemstrom B., Toppila T., Bezrukov Y. The European project FLOMIX-R: Description of the slug mixing and buoyancy related experiments at the different test facilities (Final report on WP 2). Report FZR–430, 2005, pp. 5–8.

2. Kapulla R., Dyck C., Witte M., Fokken J., Leder F. Optical flow and cross correlation techniques for velocity field calculation. *Fachtagung "Lasermethoden in der Strömungsmesstechnik"*, 8–10 September 2009, Erlangen.

3. Borisov V.F., Strukov M.A. *Sposob izmereniya rashoda teplonositelya pervogo kontura yadernogo reaktora* [Method for measuring the flow rate of the primary loop of a nuclear reactor]. Patent RF, no. 2457558, 2012.

4. Konovalov I.A., Khrobostov A.E., Legchanov M.A., Solncev D.N., Barinov A.A., Ryazanov A.V., Chesnokov A.A., Makarov M.A. Application of the Correlation Velocity Measurements for Hydrodynamic

Приборы и методы измерений
2021. – Т. 12, № 1. – С. 67–74
I.A. Konovalov et al.

Devices and Methods of Measurements
2021, vol. 12, no. 1, pp. 67–74
I.A. Konovalov et al.

Investigations of Turbulent Coolant Flow in Nuclear Reactor Elements. *Devices and Methods of Measurements*, 2020, vol. 11, no. 3, pp. 196–203. **DOI:** 10.21122/2220-9506-2020-11-3-196-203

5. Prasser H.M., Kleim S. Coolant mixing experiments in the upper plenum of the ROCOM test facility. *Nuclear Engineering and Design*, 2014, no. 276, pp. 30–42. **DOI:** 10.1016/j.nucengdes.2016.10.038

6. Dave A., Manera A., Beyer M., Lucas D., Prasser H.M. Uncertainty analysis of an interfacial area reconstruction algorithm and its application to two group interfacial area transport equation validation. *Nuclear Engineering and Design*, 2016, no. 310, pp. 30–42. **DOI:** 10.1016/j.nucengdes.2014.05.016

7. Dmitriev S.M., Khrobostov A.E., Barinov A.A., Glavnii V.G. *Razrabotka I adaptatsiya vihrerazreshayshei izmeritelnoi systemi* [Development and Adaptation of Vortex Realizable Measurement System for Benchmark Test with Large Scale Model of Nuclear Reactor]. *Devices and Methods of Measurements*, 2017, vol. 8, no. 3, pp. 203–213 (in Russian). **DOI:** 10.21122/2220-9506-2017-8-3-203-213

8. Sorokin G.A. *Filtri nizhnih chastot* [Low-pass filters]. *Vestnik Uzhno-Uralskogo gosudarstvennogo universiteta. Seriya: Computernie tehnologii* [Bulletin of the South Ural State University. Series: Computer technology, control, radio electronics], 2015, vol. 1, pp. 100–107 (in Russian).

9. Kokken J., Krohn B., Kapulla R., Niceno B., Prasser H.M., Badillo A. NEA Benchmark Exercise: Computational Fluid Dynamic Prediction and Uncertainty Quantification of a GEMIX Mixing Layer Test. *Nuclear energy agency committee on the safety of nuclear installations*, 2019, pp. 21–25.

10. Bendat J., Piersol A. Random Data: Analysis and Measurements Procedures. *Fourth Edition. John Willey & Sons*, 2012, pp. 272–274.

11. Bendat J., Piersol A. Engineering Applications of Correlation and Spectral Analysis. *Second Edition. John Willey & Sons*, 2013, pp. 274–276.