Planning an experimental study of water valves

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Abstract. Designing the plan of the experiment represents the optimal control of empirical research while processing an incomplete knowledge of the mechanism of phenomena. Experiments are usually performed in small series according to a pre-compiled algorithm, optimal in a pre-defined range. After each series of experiments, the measurement results are processed and an informed decision is made. Statistical processing of experiment data allows us to get the correct research results with errors that do not exceed the tolerance limits. The research goal is to develop a program and plan for the experimental study of the laws and quantitative values of the hydraulic characteristics of water folding valves. As a result of the research, attention is emphasized on the preliminary processing of the experiment data provided for the design of the experiment to study the hydraulic characteristics of the valves. As a part of the research of the experiment design, a program for the experimental change in water flow through the passage opening of the water valves was developed and verified. The results of the research allow us to carry out experimental studies of the hydraulic characteristics of the valves and obtain data with a given statistical security.

Keywords: measurement, water consumption, average value, gross errors, standard deviation, confidence interval.

1. Introduction
Designing the plan of an experiment is an integral part of empirical research with incomplete knowledge of the mechanism of the phenomena studied. The research [1] focuses on the fundamental aspects of experimental design: determining the purpose and scope of an experiment, differentiating between alternative types of experimental variables, understanding the underlying conditions and limitations, and conducting a phased experiment. Experiments can reveal many unexpected factors and pose questions for their further detailed study. The design of the experiment helps to detect the presence of interaction between the factors of the process, and not only to study one factor at a time [2]. A comparison of qualitative, quantitative and mixed methods of research of the project was made [3, 4].

Application of experimental design allows us to choose the right strategy for collecting the preliminary information in a short time, which will allow us to formulate the goal of the work and choose a preliminary design of experimental planning. Experiments are usually performed in small series according to a pre-compiled algorithm, optimal in a pre-defined range. After each series of experiments, the measurement results are processed and an informed decision is made on further analysis of the results [5-7].

In the articles [8-11], the results of a study of the flow rate of water folding valves with a flat washer shutoff pair are presented. The study reports on experiments and numerical modeling of the influence of the process of opening and closing a ball valve [12, 13]. The concept of a response surface methodology can be used to establish an approximate explicit functional relationship between input random variables and output response using regression and probabilistic analysis [14]. The problem of choosing the object of study with respect to solving practical problems in the design of the experiment is considered. The mathematical methods of experiment design planning are based on the cybernetic idea of the object of study [15].
The requirements for optimization and modeling of experimental designs are formulated [16]. Issues of studying random variables and random processes are considered in articles [17-19]. This is especially important while conducting hydraulic studies of units of sanitary fittings, since under practically identical experimental conditions, the measurement results are usually characterized by fluctuations in a certain range.

An analysis of the research results of specialists shows that many studies are devoted to the design of the experiment. However, the issues of an experimental study of the laws and quantitative values of the hydraulic characteristics of water folding valves have not been fully studied. The goal of the study is to develop a program and plan for the experimental study of the laws and quantitative values of the hydraulic characteristics of water folding valves and fittings. After definition of the object of study and determining the necessary accuracy of the expected measurement results in accordance with the resolution of the measuring instruments and other restrictions, mathematical planning of the experiment is carried out in relation to the specific conditions of the object.

2. Research methods

There are several methods for organizing an experiment, depending on its type: active or passive, laboratory or production. In this study, theoretical and experimental methods for studying the hydraulic characteristics of valves are used. On the basis of the theoretical method, the main aspects of the functioning of the valves are determined and the methodology of the mathematical design of the experiment is developed. In an experimental study, causal relationships of the formation of hydraulic characteristics of water folding valves and fittings are identified and refined. The mathematical planning of an experimental study has been completed. For a correct assessment of the data obtained from laboratory and field experiments and observations, it is necessary to analyze them using mathematical statistics and probability theory. Assessment of the studied value was made on the basis of confidence intervals method. Confidence intervals for estimating the average value allow us to determine the range of values in which an exact solution is likely to appear. The method of confidence intervals is based on the fact that with a given probability \( P = 1 - \alpha \) the true value of \( \alpha \) is located in a certain interval with random boundaries. A positive variable \( \delta \) is chosen so that the values that go beyond the boundary of the interval are negligibly small. Using the Laplace function [5, 6] we can write:

\[
P\left(\bar{x} - \delta < \alpha < \bar{x} + \delta\right) = 2\Phi(t)
\]

where \( t = \frac{\delta \sqrt{n}}{S} \) is the argument of the Laplace function; \( \delta \) is the accuracy of measurements; \( n \) is the sample size; \( S \) is the standard deviation.

The accuracy of the estimate \( \delta = \frac{tS}{\sqrt{n}} \) allows us to write the Laplace function in the form:

\[
P\left(\bar{x} - \frac{tS}{\sqrt{n}} < \alpha < \bar{x} + \frac{tS}{\sqrt{n}}\right) = 2\Phi(t)
\]

Since the probability \( P \) is given, we can write the inequality:

\[
P\left(\frac{\bar{x} - tS}{\sqrt{n}} < \alpha < \bar{x} + \frac{tS}{\sqrt{n}}\right) = 2\Phi(t)
\]

The minimum number of measurements \( n \) for assessing the true value \( \alpha \) of studied quantity with a given accuracy \( \delta \) and reliability \( \gamma \) is determined by the formula:
Using the Student’s distribution and the Laplace function [5, 6], we can find the confidence interval \( nSxT \gamma \pm T \), that is covering the studied parameter \( a \) with reliability \( \gamma \). Given the known accuracy of measurements and the given reliability of the expected result, it is possible to determine the required sample size using tables of \( t \)-values of the argument of the Laplace function \( \Phi(t) \) at which \( \Phi(t)=\gamma/2 \). The presented confidence estimates of the studied value of \( \alpha \) are used in the subsequent statistical processing of experiment data.

In the process of performing measurement work in experimental studies, it becomes necessary to identify gross errors in the data obtained. Abnormal values in the series of the obtained data bring in additional errors into the results of the analysis of the experimental study. In this regard, these values must be extracted from the observation matrix. Some gross errors are obvious and justification is not required to extract them. However, there are gross errors, the abnormal values of which is not obvious. In this case, mathematical justification is required to make an objective decision. For elimination of gross errors from a series of observations \( X(n) \), the Student’s distribution can be used. The critical value \( (p \text{- is the percentage point of the normalized sample deviation}) \) is expressed through of the critical value of the Student’s distribution \( \tau(p, n) \) [20, 21]:

\[
\tau = \frac{t(p, n)\sqrt{(n-1)}}{\sqrt{(n-2)+t^2(p, n)}} \tag{5}
\]

The decision on the necessity of eliminating the abnormal value is made on the basis of comparing the statistics \( \tau \) with the critical value by the formula (5). The observed value of statistics \( \tau \) is determined by the formula:

\[
\tau = \frac{|x_i - \bar{x}|}{S} \tag{6}
\]

where \( x_i \) - is the extreme (largest or smallest) element of the sample by which \( \bar{x} \) and \( S \) was calculated; \( \bar{x} \) - is the average value of the sample; \( S \) - is the standard deviation of the sample; \( \tau \) - is the value of the statistics \( \tau \), calculated with a confidence probability \( q=1-p \).

If the abnormal sample value is confirmed, then it will be deleted, and the statistical parameters of the sample are recalculated.

After selecting the object and determining the necessary accuracy of the expected measurement results in accordance with the resolution of the measuring instruments and other imposed restrictions, mathematical planning of the research is carried out in relation to the specific conditions of the object.

3. Results and discussion

The study involves bench testing of valves with a flat washer stop pair. The locking pair has a bore in the form of a semicircle. The measurement uses water flow through the bore hole at a pressure of 0.05 MPa. The standard deviation is determined based on preliminary measurements as \( S=0.0065 \) l/s. The accuracy of water flow measurements is \( \delta =0.005 \) l/s. The minimum number of measurements is determined provided that \( \gamma=0.95 \). The Laplace function \( \Phi(t)=0.95/2=0.475 \). Then, according to the table of the Laplace function [5, 6], \( t=1.96 \). According to the formula (4), the minimum number of measurements at one turning point of the handle is determined:

\[
n = \left( \frac{1.96 \times 0.0065}{0.005} \right)^2 = 6.4 \approx 6
\]
Thus, the desired measurement sample size is $n \approx 6$. Preliminary statistical data processing was performed in accordance with the methodological algorithm (Figure 1).

![Figure 1](image.png)

**Figure 1.** Scheme of the methodological algorithm for statistical processing of experiment data

An example of preliminary statistical processing data is presented in table 1.

| Handle turn angle (degrees) | 0  | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 |
|-----------------------------|----|----|----|----|----|-----|-----|-----|-----|-----|
| Water consumption (l/s)     | 0.0 | 0.006 | 0.009 | 0.033 | 0.042 | 0.048 | 0.058 | 0.049 | 0.048 | 0.046 |
|                             | 0.0 | 0.005 | 0.009 | 0.034 | 0.025 | 0.028 | 0.045 | 0.050 | 0.060 | 0.062 |
|                             | 0.0 | 0.005 | 0.008 | 0.029 | 0.037 | 0.042 | 0.051 | 0.042 | 0.052 | 0.050 |
|                             | 0.0 | 0.006 | 0.007 | 0.030 | 0.040 | 0.052 | 0.063 | 0.063 | 0.065 | 0.066 |
|                             | 0.0 | 0.005 | 0.008 | 0.031 | 0.039 | 0.045 | 0.054 | 0.054 | 0.056 | 0.056 |
|                             | 0.0 | 0.005 | 0.008 | 0.020 | 0.038 | 0.035 | 0.037 | 0.039 | 0.040 | 0.040 |
| Average value (l/s)         | 0.0 | 0.005 | 0.008 | 0.029 | 0.037 | 0.042 | 0.051 | 0.051 | 0.052 | 0.053 |
| Standard deviation          | 0.0 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Minimum value               | 0.0 | 0.005 | 0.007 | 0.020 | 0.025 | 0.028 | 0.037 | 0.039 | 0.040 | 0.040 |
| Maximum value               | 0.0 | 0.006 | 0.009 | 0.034 | 0.042 | 0.052 | 0.063 | 0.063 | 0.065 | 0.066 |
| Confidence interval         | 3.8E- | 4.0E- | 4.9E- | 7.0E- | 7.5E- | 7.5E- | 7.7E- | 7.5E- | 6.6E- | 7.8E- |
| The variation coefficient (%)| 8.70 | 10.09 | 16.95 | 16.53 | 21.14 | 18.27 | 18.81 | 16.03 | 18.37 |
3.1. Check sampling for gross measurement errors

The procedure for checking the sample for gross errors is based on Student’s statistics. The specified procedure provides for the following actions:

1. Calculation of the average value of the sample \( \bar{x} \).
2. The calculation of the standard deviation for the sample \( S \).
3. Select the data that has the largest or smallest value from the table of the measurement protocol.
4. Calculate the values of the observed statistics \( \tau \) by the formula (6).
5. Using the formula (5), calculate the corresponding points:
   \[
   \tau_{5\%}, \tau_{0.1\%}
   \]
6. Compare the obtained values: \( \tau \leq \tau_{5\%} \) - the data are not abnormal; \( \tau_{5\%} \leq \tau \leq \tau_{0.1\%} \) - can be eliminated, if there are other considerations of the researcher; \( \tau > \tau_{0.1\%} \) - such data is usually always discarded.

An example of the detection of abnormal values in the samples is presented in table 2.

| Handle turn angle (degrees) | 0  | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 |
|----------------------------|----|----|----|----|----|-----|-----|-----|-----|-----|
| \( \tau \) | 0.0 | 1.71 | 1.16 | 0.90 | 0.85 | 1.19 | 1.26 | 1.25 | 1.58 | 1.27 |
| \( \tau_{5\%} \) | 0.0 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 |
| \( \tau_{0.1\%} \) | 0.0 | 2.12 | 2.12 | 2.12 | 2.12 | 2.12 | 2.12 | 2.12 | 2.12 | 2.12 |

An analysis of checking the results for the presence of abnormal values in the samples shows that the measured value of the water consumption rate when the handle is rotated by 20° can be accepted as abnormal. By comparing the observed statistics and critical values of Student’s statistics, it was decided to perform additional measurements of water flow when the handle is rotated by 20°.

Satisfaction of the obtained results with the drawn up plan provides the basis for a technical and economic analysis and the development of sound conclusions and recommendations.

4. Conclusions

This research focuses on the preliminary processing of experimental data provided for in the design of an experiment to study the hydraulic characteristics of valves. Statistical processing of experiment data allows us to get the correct research results with errors that do not exceed the tolerance limits. The following results were obtained in the framework of the experiment design planning study:

1. The developed program has been verified by the example of an experimental study of the change in water consumption through the bore of the water folding valves.
2. Verification of method of the statistical analysis of data confirmed its effectiveness in experimental research of an applied nature.

An experimental study of water-folding valves and fittings in accordance with the developed plan allows to obtain results with a security of at least \( \alpha = 0.05 \).

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6. References

[1] Anderson V L and McLean R A 2018 Design of experiments: a realistic approach (New York: Marcel Dekker)
[2] Wahid Z and Nadir N 2013 Improvement of one factor at a time through design of experiments World Appl. Sci. J. 21 56-61
[3] Creswell J W and Creswell J D 2017 Research Design: Qualitative, Quantitative, and Mixed Methods Approaches (California: SAGE Publications)

[4] Creswell J W and Plano Clark V L 2017 Designing and Conducting Mixed Methods Research (California: SAGE Publications)

[5] Gmurman V E 2014 Probability theory and mathematical statistics (Moscow: Publication house Urite) p 478 https://avidreaders.ru/book/teoriya-вероятностей-i-matematiceskaya-statistika-12.html

[6] Colin R 2002 Mathematical statistics with Mathematica (Springer)

[7] Brown G T L 2017 Doctoral Education in Quantitative Research Methods: Some Thoughts about Preparing Future Scholars Front. Appl. Math. Stat. 3 doi: 10.3389/fams.2017.00025

[8] Svintsov A P, Kharun M and Mukarzel S A 2015 Valve head for water fittings with high regulatory capacity Magazine Civ. Eng. 58(6) 8-18

[9] Svintsov A P, Mukarzel S A and Kharun M 2016 Method of Determining the Orifice Area of Valve Head Locking Pairs of Water Fittings J. Urban and Environmental Eng. 10(1) 57-61

[10] Svintsov A P and Konoplev N A 2018 Hydraulic characteristics of tap valve with a flat closure member J. Urban and Environmental Eng. 12(2) 231-35

[11] Svintsov A P and Konoplev N A 2019 Hydraulic Characteristics of the Locking Element in the form of a “Curved Drop” for Water Supply Fittings J. Mechanics of Continua and Mathematical Sci. 18 527–36

[12] Cui B, Lin Z, Zhu Z, Wang H and Ma G 2017 Influence of opening and closing process of ball valve on external performance and internal flow characteristics Experimental Thermal Fluid Sci. 80 193-202

[13] Tao J, Lin Z, Ma C, Ye J, Zhu Z, Li Y and Mao W 2020 An Experimental and Numerical Study of Regulating Performance and Flow Loss in a V-Port Ball Valve ASME. J. Fluids Eng. 142(2) 021207

[14] Morshedi A and Akbarian M 2014 Application of response surface methodology: design of experiments and optimization: a mini review J. Fund. Appl. Life Sci. 4(S4) 2434-39

[15] Radnaev D N, Zimina O G and Badmatsyrenov D-C B 2019 Analysis and selection of the research object in solving scientific and technical problems ESSUTM Bulletin 3(74) 63-8

[16] Radchenko S G 2013 Multi-factor experiment plans for joint optimization and simulation Mathematical machines and systems 3 124-30

[17] Govorukha P A 2018 Statistical Analysis of the Multifactor Experiment Results to Evaluate Organizational and Technological Solutions for Enclosure Structures Sci. business: Constr. arch. 4(82) 43-6

[18] Kovel A A 2019 Prognostic potential of mathematical experiment planning Space vehicles and technol. 2(28) 87-93

[19] Bessonov A S 2019 Research Methodology and Design of Experiments Prospects Sci. 4(115) 63-5

[20] Zhang Q B and Zhao J 2013 A Review of Dynamic Experimental Techniques and Mechanical Behaviour of Rock Materials Rock Mechanics and Rock Engineering 47 1411–1478

[21] Lvovsky E N 1982 Statistical methods for constructing empirical formulas (Moscow: Publishing house Higher School)