ТРАНСПОРТНЫЕ СИСТЕМЫ
2.9.1 – Транспортные и транспортно-технологические системы страны,
ее регионов и городов, организация производства на транспорте;
2.9.4. – Управление процессами перевозок;
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Experimental investigation and optimization of a check filter element for the dynamic measurement method of aviation fuel industrial cleanliness level

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Abstract: Ensuring the cleanliness of aviation fuel from mechanical impurities is a critical factor in flight safety. Existing laboratory methods for monitoring fuel cleanliness are discrete and do not allow for the prompt detection of contaminants during aircraft refueling, which creates significant risks. The objective of this study was to experimentally investigate and optimize the parameters of a partial-flow control filter to create a system for continuous, real-time monitoring of aviation fuel cleanliness. The key diagnostic parameter in this study was the pressure drop across the filter element, which directly correlates with the amount of accumulated mechanical impurities. A combination of experimental and analytical methods was used in the study: bench tests were conducted on corrugated polypropylene filter elements with varying surface areas, during which the dependence of the pressure drop on the mass of the introduced contaminant (kaolin mixture) was measured. This resulted in the dependence of the pressure drop on the specific contaminant capacity. It was found that this dependence has four characteristic zones: an initial linear zone, where the pressure drop increases proportionally to the contamination, and three nonlinear zones, where the rate of pressure drop increase significantly as the pores of the filter element become clogged. A parametric study was conducted using this experimental curve, which showed that for optimal filter operation, its filtration area should be 0.05–0.10 m². Based on this study, a system for operational monitoring of aviation fuel cleanliness using a check filter was proposed. This ensures not only a long service life (200–400 refuelings) but also high system sensitivity: the estimated response time to exceeding the rejection level of contamination averages 5–10 seconds, which is determined by the rate of change in the pressure drop upon the influx of impurities. The practical feasibility of using a check filter, where the pressure drop serves as a reliable and informative parameter for creating a system for promptly warning of aviation fuel contamination directly during refueling, was proved.

Keywords: aviation fuel, fuel cleanliness, mechanical impurities, continuous monitoring, check filter, partial-flow filter, experimental study, parameter optimization, contaminant capacity, pressure drop.

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Экспериментальное исследование и оптимизация параметров контрольного фильтроэлемента для метода динамических измерений уровня промышленной чистоты авиатоплива

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Аннотация: Обеспечение чистоты авиационного топлива от механических примесей является критически важным фактором безопасности полетов. Существующие методы лабораторного контроля чистоты топлива носят дискретный характер и не позволяют оперативно выявлять загрязнения в процессе заправки воздушных судов, что создает серьезные риски. Целью данной работы было экспериментальное исследование и оптимизация параметров неполнопоточного контрольного фильтра (КФ) для создания системы непрерывного мониторинга чистоты авиатоплива в реальном режиме времени. Ключевым диагностическим параметром в настоящем исследовании выступил перепад давления на фильтроэлементе (ФЭ), который напрямую коррелирует с количеством накопленных механических примесей. В ходе работы был использован комплекс экспериментальных и аналитических методов: проведены стендовые испытания гофрированных полипропиленовых ФЭ с различной площадью поверхности, в ходе которых измерялась зависимость перепада давления от массы подведенного загрязнителя (смеси каолинов). В результате была получена зависимость перепада давления от удельной грязеемкости. Было выявлено, что эта зависимость имеет четыре характерные зоны: начальную линейную, где перепад давления растет пропорционально загрязнению, и три нелинейные, где скорость роста перепада давления существенно увеличивается по мере закупорки пор ФЭ. На основе этой экспериментальной кривой было проведено параметрическое исследование, которое показало, что для оптимальной работы КФ его площадь фильтрации должна составлять 0,05–0,10 м^2. На основании исследования предложена система оперативного контроля чистоты авиатоплива с использованием контрольного фильтра, что обеспечивает не только высокий ресурс (200–400 заправок), но и высокую чувствительность системы: расчетное время реакции на превышение браковочного уровня загрязненности составляет в среднем 5–10 с, что определяется скоростью изменения перепада давления при поступлении примесей. Доказана практическая целесообразность использования контрольного фильтра, где перепад давления служит надежным и информативным параметром для создания системы оперативного предупреждения о загрязнении авиатоплива непосредственно в процессе заправки.

Ключевые слова: авиационное топливо, чистота топлива, механические примеси, непрерывный мониторинг, контрольный фильтр, неполнопоточный фильтр, экспериментальное исследование, оптимизация параметров, грязеемкость, перепад давления.

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Introduction

Ensuring flight safety is one of the primary objectives of all companies involved in the flight operations and ground handling of civil aviation aircraft. Refueling systems, which supply aircraft with high-quality aviation fuels and lubricants, directly impact flight safety [1].

The quality of aviation fuel is largely ensured by settling, filtration, and the addition of special additives. This entire complex of measures helps maintain the concentration of mechanical impurities and the size of contaminants in compliance with regulatory requirements. The development of devices that measure and indicate the level of mechanical impurities in aviation fuel directly during its transfer and refueling into aircraft is one of the most pressing areas for improving the aviation fuel supply process.

According to the current regulatory documentation, aviation fuel quality control is conducted by laboratory analysis of samples based on established parameters, as well as rapid visual inspection. Aviation fuel sampling is carried out along the entire path of its movement, from the supplier's receiving area to the aircraft's fuel tanks. The sampling points are confined to the areas of the most likely accumulation of mechanical impurities and free water (the lower points of pipelines and tanks of fuel tankers, filter settling tanks, etc.).

The reception, storage, transferring and refueling of aviation fuel in aircraft is accompanied by both the processes of its purification from mechanical impurities – filtration and settling – and the processes of contamination by particles of wear and corrosion of equipment, as well as atmospheric dust entering through breathing devices. Due to the continuous nature of these processes, point samples, in terms of time and location, have a limited reliability limit for assessing the cleanliness of jet fuel. In some cases, this can critically impact the safety of the aircraft. Refueling aircraft poses a particular risk. The final cleaning device in this process is the fueler's filter-water separator (FWS). If the FWS filtration capacity is reduced, the quantity and/or size of solids may exceed the specified limit. Damaged FWS filter elements, as well as wear debris from hoses, the meter, and other components located between the FWS and the underwing refueling nozzle, can cause uncontrolled fuel contamination during aircraft refueling.

Main Part

To address this issue, several methods and devices for continuous monitoring of mechanical impurities have been proposed [2]. For example, Parker MCM20[1] particle counter or the Velcon VCA[2] [3] fuel contamination analyzer, which use laser flow scanning; the Potok-RT indicator in the "ZOND" modification[3], the operation of which is based on the photoelectric effect [4]. Devices [5, 6] have also been proposed, the operation of which is based on the known dependence of the pressure drop across a partial-flow check filter on the mass of the pollutant supplied to it.

The use of a check filter, based on well-studied filtration laws [7, 8], appears to be a reliable and valid method.

A diagram of the use of a check filter in a fuel tanker is shown in Figure 1.

Aviation fuel, including a mixture with fuel system icing inhibitor (FSII), is sampled at the check filter downstream of the flow meter. At the sampling point, the pressure is regulated by an in-line valve and, depending on its setting, is typically between 0.35 and 0.38 MPa. After passing the check filter, the flow is directed to the inlet of the fuel tanker pump, where the pressure is always near-zero, except for brief periods during startup and shutdown. The maximum pressure drop across the check filter will be reached when it is completely clogged and will be equal to the fueling pressure.

If the relationship between the pressure drop across the filter and the amount of contaminant supplied to it is known, then, based on the pressure drop measured over a certain time interval, the number of mechanical impurities entering the filter during this period can be calculated. Further, by measuring the volume of aviation fuel passing through the filter during the measurement period, the concentration of mechanical impurities in it can be determined. It is advisable to assign these calculations to a microprocessor.

For the practical and economically feasible implementation of a check filter, it is necessary to select its filter element that provides an optimal ratio of contaminant capacity and sensitivity to the level of contamination of aviation fuel. The problem with this choice is that filter manufacturers provide hydraulic characteristics only for a clean filter element, taken during testing with purified liquid. For example, with reverse

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[1] Catalog: FDHB500UK 04/2010. (2008). Hannifin Corporation, 45 p.

[2] Velcon Contaminant Analyzer. Technical description. Available at: https://thermalsolutionsoftexas.com/pdfs/filtration/parer-velcon-clean-diesel-vca-series-contaminant analyzerdatasheet.pdf (accessed: 12.03.2025).

[3] Aviation Fuel Cleanliness Indicator. Industry-Specific Research Laboratory ONIL-16. Available at: http://onil-16.ssau.ru/potokrtr.html (accessed: 12.03.2025).

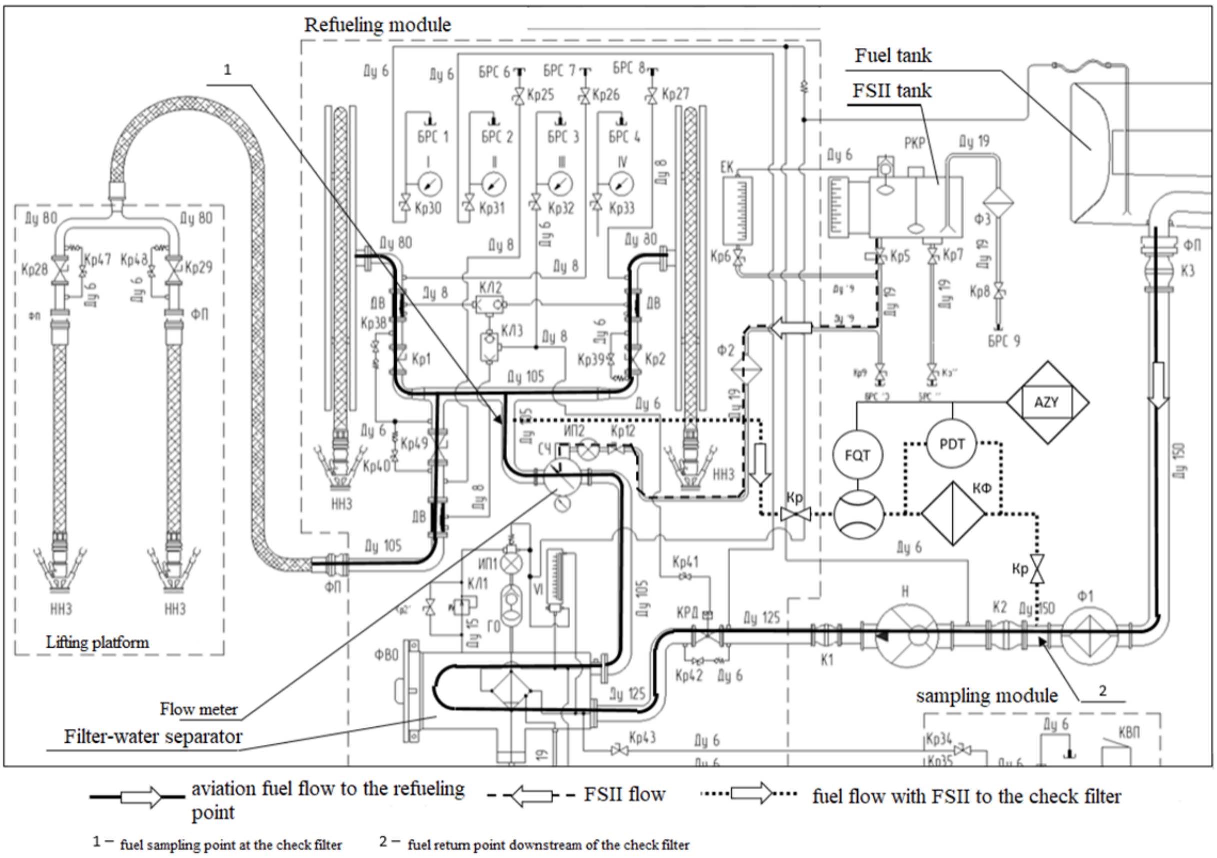

Fig. 1. Diagram of fuel and FSII flow in a refueling module using a check filter:
КФ – Check Filter; *FQ* – Flow Meter; *PDT* – Pressure Differential Transmitter; *AZY* – Computing Unit; *Кр* – Valve

osmosis wate[4] [9]. Therefore, the hydraulic characteristic of a partially contaminated filter element can only be obtained experimentally.

The aim of this study was to experimentally determine the dependence of the pressure drop across a filter element on the mass of contaminant applied to a unit of its area and to select the optimal filter element parameters using the obtained characteristics. The best filter element can be considered one with the maximum service life and sufficient sensitivity to the maximum permissible level of mechanical impurities.

In this study, service life is defined as the volume of aviation fuel loaded into an aircraft by a refueller during the period of use of the check filter.

The sensitivity of the check filter is defined as the time required to reliably determine the rejection level of mechanical impurities of 2 g/t[5] [10].

Parameters selected for the check filter: nominal filtration fineness, area, jet fuel flow rate, supply line diameter, and differential pressure sensor accuracy.

When selecting the filter element and planning the experiment, the following considerations were taken into account.

1. A volumetric filtration filter element typically has a higher contaminant capacity than

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[4] Deep filter elements (pre-filters) of the EPVg.P brand. RPE “Technofilter”: catalog of filtration equipment. Available at: https://www.technofilter.ru/catalog/patronnyefiltry/glubinnye-filtruyushchie-elementypredfiltry/epvg-p/ (accessed: 12.03.2025).

[5] Order of the Ministry of Transport of the RSFSR of October 17, 1992 No. DV-126 “On the Implementation of the Manual for the Reception, Storage, Preparation for Refueling, and Quality Control of Aviation Fuels, Lubricants, and Special Fluids in Civil Aviation Enterprises of the Russian Federation”. GARANT, 114 p. Available at: https://base.garant.ru/71539730/ (accessed: 12.03.2025).

Fig. 2. External view of the filter components
а – External view of the replaceable filter elements; *б* – Filter holder

a surface filtration filter element (with the same nominal filtration rating and effective filter area). However, it may differ in that the hydraulic characteristic measured on the contaminated liquid may be more dependent on the particle size distribution of the contaminant.

2. Using a filter element with a maximum pressure drop slightly higher than the filling pressure allows for the safe use of its full contaminant capacity.
3. The flatter the hydraulic characteristic of a clean filter element, the greater the available pressure drop range and, consequently, the longer the service life of the check filter.
4. The nominal filtration rating of the control filter must be equal to or less than the nominal filtration rating of the monitored filter-water separator.
5. The filter element must be compatible with jet fuels and FSII.
6. The filter element must be manufactured in the Russian Federation.

Taking into account the possibility of using the test results in fuel tankers with a capacity of 500 to 2500 l/min, with a nominal filtration fineness of 3 µm and a filling pressure of 0.35–0.38 MPa, as a result of an analysis of possible options, corrugated filter elements based on polypropylene were selected for the experiment (fig. 2).

Table 1

List and characteristics of the filter elements used in the experiment

Serial number	Nominal filtration rating, µm	Registered filtration area, m^2	Maximum pressure, MPa
291442	2.0	0.34	0.5
507955	2.0	0.45	0.5
507956	2.0	0.45	0.5
532044	2.0	0.21	0.5
532046	2.0	0.24	0.5
556624*	2.0	0.43	0.5

* A diverting layer of increased rigidity.

The experimental setup diagram is shown in Figure 3.

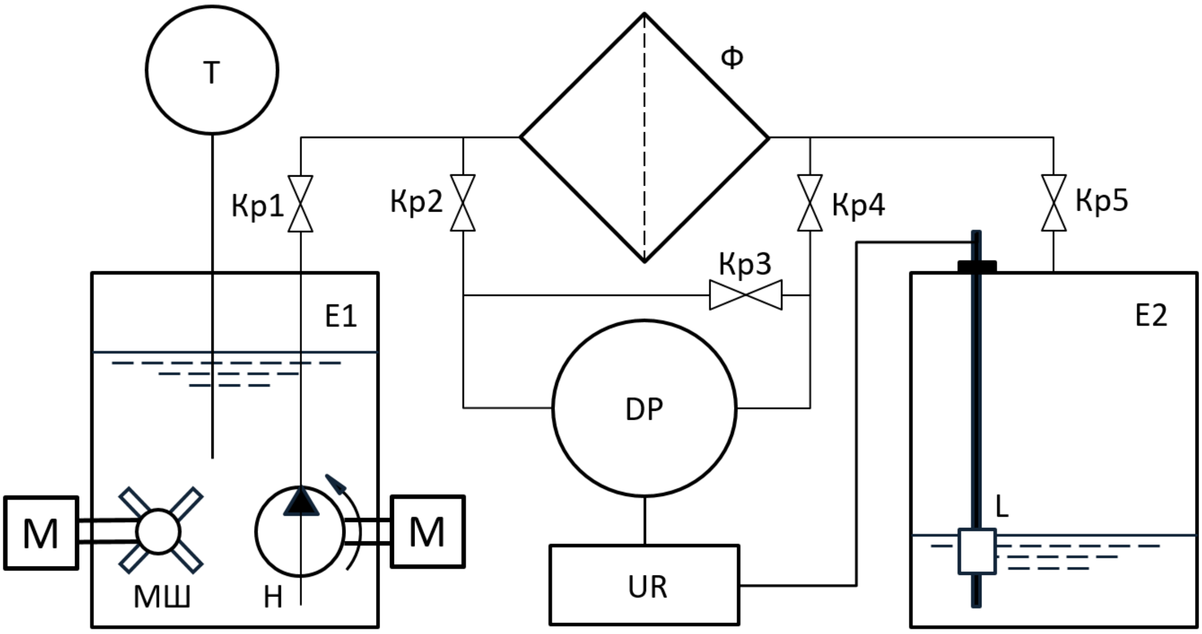

Fig. 3. Schematic diagram of the test stand for filter elements:
E1 – Supply tank; *E2* – Calibrated collection tank; *Φ* – Tested filter element; *DP* – Differential pressure sensor; *L* – Float level gauge; *T* – Laboratory thermometer; *UR* – Video recorder; *H* – Pump; *МШ* – Agitator; *Кр1...Кр5* – Valves

Fig. 4. Differential pressure sensor

To measure the pressure drop, a ZOND-20Exi-DD-K4I-78-(0…250)-kPa-42-0.15-(+5…+25)-SVM-Fl-0.5MPa-TS-1 GOST 10227-2013 (−25…+35°C) sensor was used (fig. 4).

For fire safety reasons, the filter element was tested with water. At an average water temperature of 20 °C in the experiment, the dynamic viscosity of TS-1 fuel, calculated according to GOST 10227-2013[6] [11] and water [11] differed by no more than 4%. Since dynamic viscosity is the only physical characteristic of a liquid included in the filtration equation (Darcy's law) [8], such a substitution of the test liquid seems acceptable. Furthermore, comparative tests of the filtration capacity of the tested filter elements with water and TS-1 fuel, performed by the filter

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[6] GOST 10227-2013. (2014). Jet Engine Fuels. Specifications. Moscow: Standartinform, 34 p.

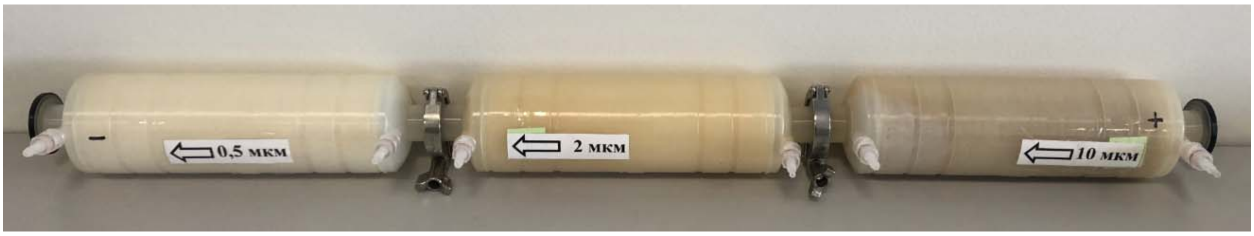

Fig. 5. Water treatment filter

element manufacturer at our request on their own setup, showed identical results.

Water for testing was prepared by double filtration through a three-stage filter with a nominal filtration fineness of the first stage of 10 μm, the second stage of 2 μm, and the third stage of 0.5 μm (fig. 5).

The authors' works [1, 12, 13] describe the sources and chemical composition of mechanical particles detected in aviation fuel at various stages of its transportation, storage, preparation, and delivery for refueling. Data on contaminants are summarized in Table 2.

Table 2

List of contaminants

Name	Density, g/cm^3
Steel (shavings)	7.85
Iron oxide FeO (wustite), black	5.70
Iron oxide Fe_3O_4 (magnetite), black	5.20
Iron oxide Fe_2O_3 (hematite), red	5.24
Sand (silicon dioxide)	2.60–1.96
Clay (kaolin)	2.60
MBS Rubber (rubber wear)	1.60
Cellulose (fibers)	1.50
Phenolic resin	1.38–1.25
Acrylic resin	1.25–1.20
Epoxy resin	1.25–1.16

Kaolin with a density of 2.58 g/cm^3 was used in filter element testing[7], which is a common contaminant of aviation fuel and enters it with atmospheric air through breathing devices.

With a nominal filtration rating of the filter-water separator of 3 μm, particles sized 3 μm and smaller may be present in the fuel flow downstream of an undamaged filter. If the filter-water separator is damaged, particles larger than 3 μm may be present. In the experiment, the contaminant was a mixture consisting (by weight) of 30% delaminated kaolin with a nominal particle size of 3 μm[8] and 70% micronized kaolin with a nominal particle size of 2 μm[9]. Based on the manufacturer's data on the particle size distribution of kaolins, the calculated particle size distribution of the test pollutant is presented in Figure 6.

The pollutant was weighed on an electronic scale with an accuracy of 0.01 g.

The pollutant was added to the test fluid in accordance with the recommendations of GOST 14146-88[10].

The fluid flow rate in the experiment was selected so that the filtration rates in the test filter and the intended check filter were equal.

Therefore, it is advisable to reduce the flow rate to a limit limited by the representativeness of the particulate matter content per unit volume.

The flow rate at the sampling point (fig. 1) cannot exceed 5 m/s. In practice, for different fuel tankers it ranges from 4.1 to 4.8 m/s, which corresponds to Re numbers in the range (170,000…400,000) >> 4000. Consequently,

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[7] Kaolin. Batolit: Milled and finely dispersed fillers. Available at: http://www.batolit.ru/154_p.shtml (accessed: 12.03.2025).

[8] Delaminated kaolin. Batolit: Milled and finely dispersed fillers. Available at: http://www.batolit.ru/157_p.shtml (accessed: 12.03.2025).

[9] Micronized kaolin. Batolit: Milled and finely dispersed fillers. Available at: http://www.batolit.ru/288_p.shtml (accessed: 12.03.2025).

[10] GOST 14146-88. (1988). Diesel Fuel Filters. General Technical Devices. Moscow: Standards Publishing House, 22 p.

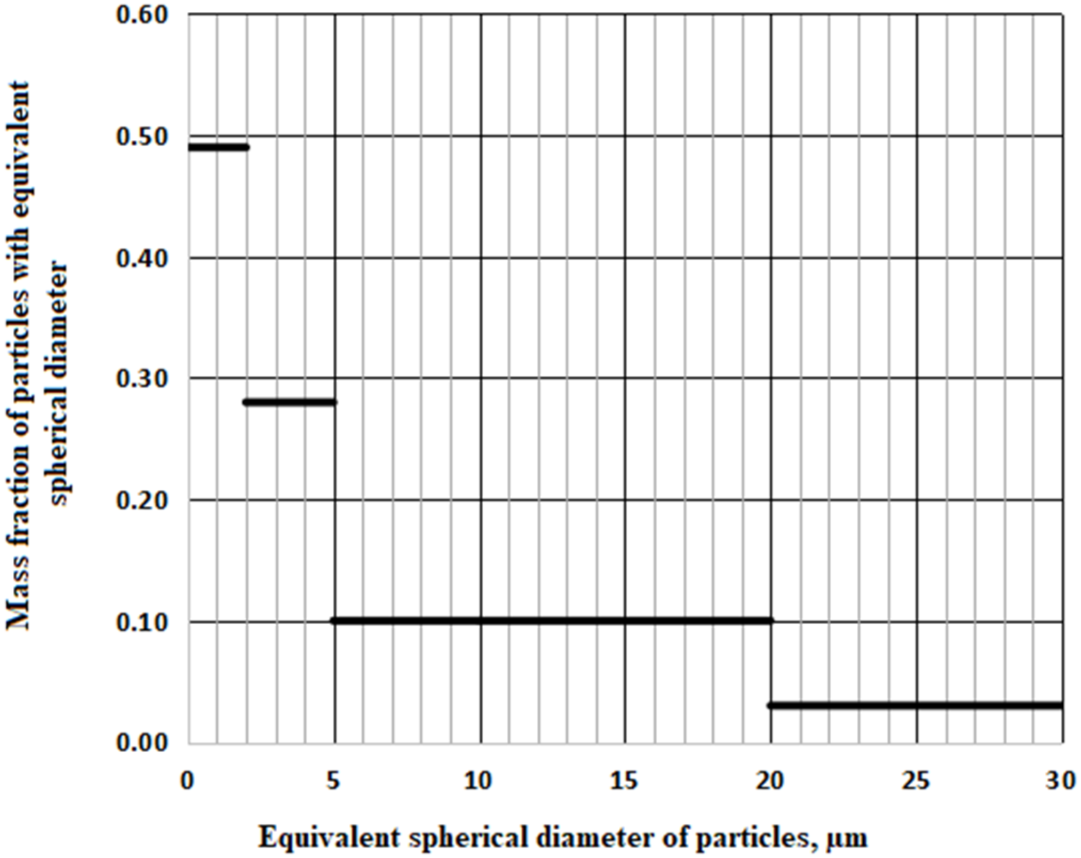

Fig. 6. Particle size distribution of the test contaminant

there is a developed turbulent flow [11] with intensive movement of liquid particles across the flow. In this case, the dynamic pressure is more than 13 kPa. According to GOST 17216-2001[11] the maximum particle size in liquids of 4...8 cleanliness classes, corresponding to aviation fuel contamination from 0.2 mg/l to 2 g/t, should not exceed 200 µm. A study [1] of the separating elements of a fuel tanker filter-water separator showed a maximum particle size of 62 µm. The hydrodynamic force acting on a particle with a diameter of 200 µm at a dynamic pressure of 13 kPa is approximately 0.05 N. The force of gravity acting on such a particle, with a density of 1.20–7.85 g/cm^3, is approximately 0.0002–0.0007 N, i.e., at least 70 times less. Consequently, even with a horizontal pipeline, turbulent movement of mechanical impurity particles will occur, and their concentration will be approximately the same at all points in the pipeline cross-section.

According to IATA regulations[12], the precautionary level of contamination of aviation fuel with mechanical impurities is 0.2 mg/liter. This corresponds to cleanliness classes 4–5 according to GOST 17216-2001, recalculated based on the particle size distribution of a pollutant with a density of 7.85–2.60 g/cm^3. Thus, at a warning level of contamination, the number of particles 5 µm or larger in size present in 100 cm^3 of fuel will be at least 390…780, and their total number will be two orders of magnitude greater. Accordingly, the average distance between particles 5 µm or larger in size will be no more than 6.3 mm, and for all particles ~ 0.1…0.2 mm. Consequently, flow sampling at the check filter with a tube with an internal diameter of 8…12 mm should ensure that the particle size

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[11] GOST 17216-2001. (2008). Industrial cleanliness. Liquid purity classes. Moscow: Standartinform, 15 p.

[12] Aviation Fuel Quality Control and Operating Procedures for Joint Into-Plane Services. 10th ed. (JIG 1). (2008). JIG (Joint Inspection Group), 108 p.

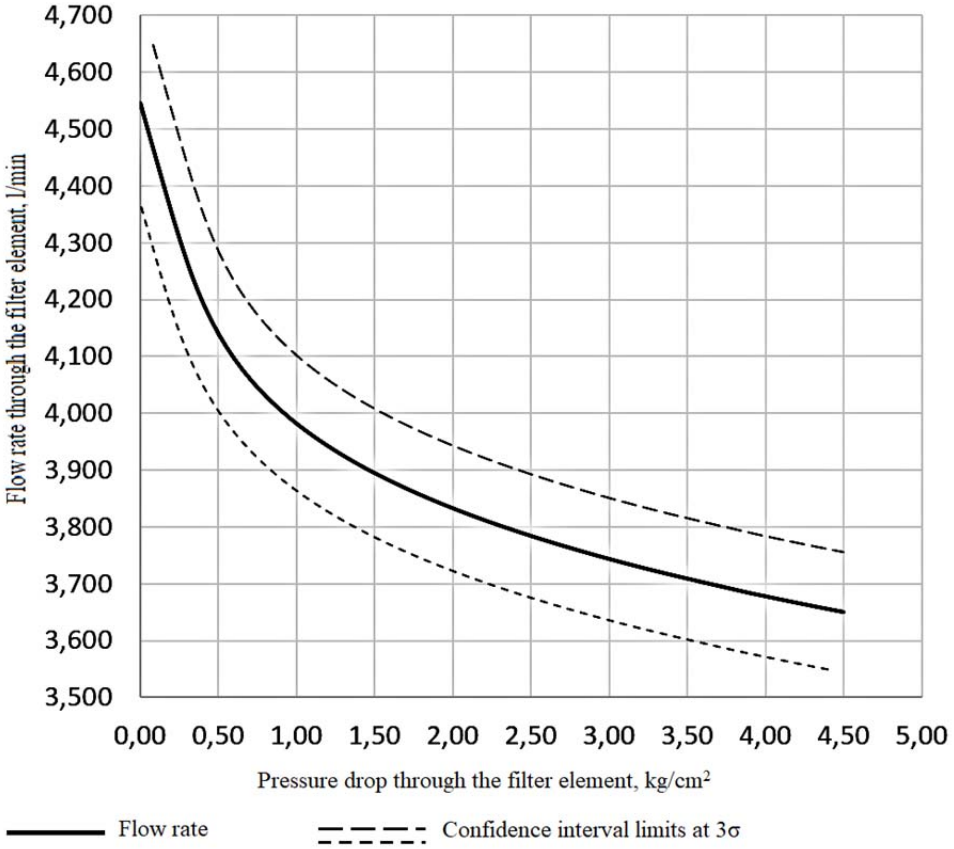

Fig. 7. Test fluid flow rate

distribution of the control flow is identical to that of the fuel being filled.

It is reasonable to limit the minimum flow velocity in the control tube to Re = 4000, the boundary of the turbulent nature of the flow [11], which minimizes particle deposition on the tube walls. For diameters of 8…12 mm, the corresponding velocity will be 0.6…0.4 m/s, and the flow rate will be 2…3 l/min. To ensure high sensitivity of the check filter, it is recommended to use a filter element with an area of 0.2 m^2 or less. In this case, the filtration rate through the check filter will not exceed 0.40 mm/s. In the experiment, the liquid flow rate was in the range of 3.5…4.7 l/min (fig. 7), and the filtration area was 0.21...0.45 m^2, which ensured the same filtration rate of 0.15…0.40 mm/s, and, consequently, the hydrodynamic similarity of the suspended matter flow in the filter element.

The experimental procedure consisted of pumping a test fluid of known contamination through the filter element in portions of 170…175 liters. Pumping ceased when a pressure drop of 4.5 kg/cm² was reached. The primary measured values were:

- pressure drop (Pf, kg/cm²) across the filter element as a function of time (t, s) – Pf(t);
- volume (V, l) of fluid pumped through the filter element as a function of time – V(t).

Next, the mass of contaminant applied to 1 m² of the filter element surface (mf, g/m²) was calculated as a function of time – mf(t):

$$mf(t) = V(t) \cdot mv / Sf,$$

where mv is the contaminant concentration, g/l; Sf is the rated effective area of the filter element, m.

Then, the desired filter element characteristic was constructed: the mass of pollutant applied to

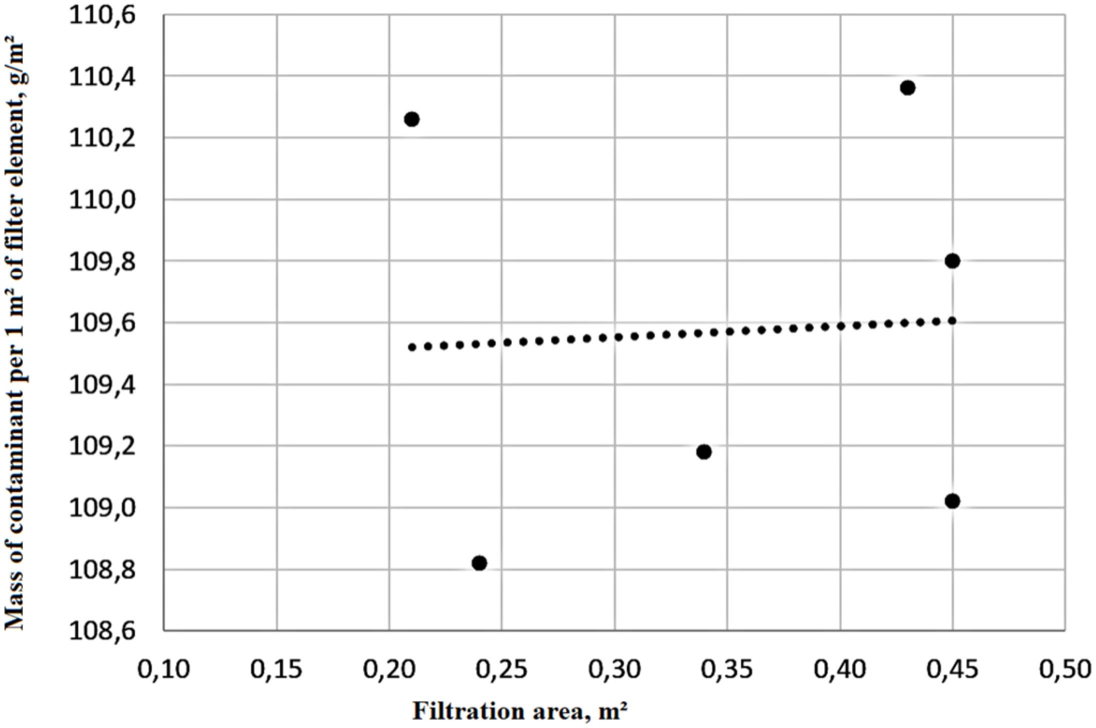

Fig. 8. Specific contaminant capacity of the FE at a pressure loss of 4.5 kg/cm²

1 m² of surface area as a function of pressure drop: mf(Pf).

Additionally, by differentiating the V(t) function using the two-way difference method, the flow rate (Q, l/min) through the filter element was calculated.

The interpretation of measurements and calculations were performed with a period of 30 s.

The pressure drop across the filter element was measured using a ZOND-20 sensor with a basic relative error of 0.15% and a measurement range of 0…250 kPa. To perform measurements in the 250…450 kPa range and reduce measurement error, the following measurement scheme was used:

- in the 0…~230 kPa range, measurements were taken with valves Kp2 and Kp4 open and Kp3 closed (fig. 3); that is, the negative chamber of the sensor was connected to the filter element outlet;
- when the pressure drop reached ~230 kPa, Kp4 closed and Kp3 opened. A pressure of ~230 kPa was supplied to the negative chamber, which became the “reference” pressure and was locked by closing Kp3 and Kp4;
- in the 230…450 kPa range, measurements were taken with valve Kp2 open and Kp3 and Kp4 closed.

To determine the pressure loss in the communication section between the differential pressure sensor connection points, the pressure drop was measured in the filter holder without a filter element at a test fluid flow rate of 4.5 l/min. It was (0.40 ± 0.12) kPa, which was taken into account in subsequent calculations and graph plotting.

The filter elements listed in Table 1 were tested. Filter element tests were conducted at pollutant concentrations of (0.2; 1.0; 1.6; 50.0) g/m³. A concentration of 50 g/m³ was used to quickly plot individual sections of the mf (Pf) characteristic. Tests of other filter elements in these sections were also conducted at concentrations of (0.2; 1.0; 1.6;) g/m³.

Figure 8 shows the dependence of the specific contaminant capacity of a filter element on the effective filtration area (hereinafter, for brevity, “specific contaminant capacity” refers to the mass of contaminant per 1 m² of the filter element).

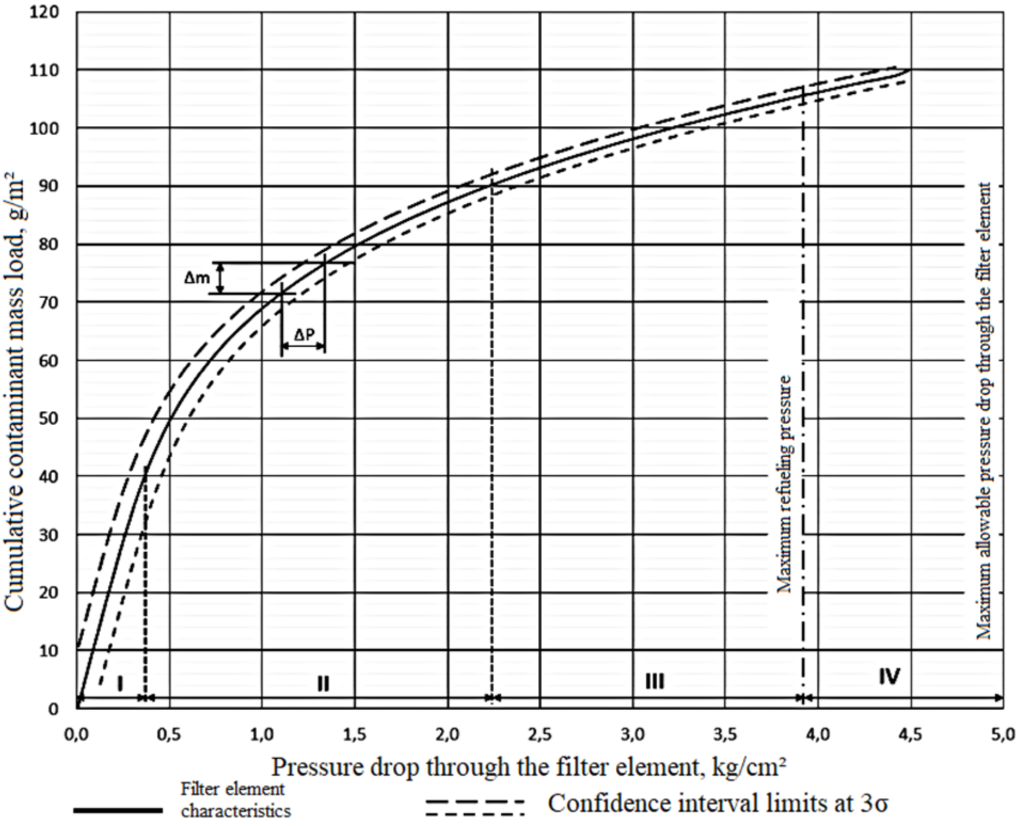

Fig. 9. Filter element characteristic mf (Pf):
ΔP – Change in the pressure differential across the FE over time Δt;
Δm – Change in the mass of contaminant supplied to 1 m² of the filter element

Across the studied range of filtration areas, the specific contaminant capacity of the filter elements (mf, g/m²) was constant. No effect of contaminant concentration, filter material batch, or filter element backing layer hardness on the specific contaminant capacity was observed.

Figure 9 shows the dependence of the specific contaminant capacity of the filter element on the pressure drop.

For safe use of the check filter, the maximum pressure of the filter element should be slightly higher than the maximum filling pressure. Filter elements with a maximum pressure of 0.5 MPa were used in the experiment.

The graph in Figure 9 distinguishes four characteristic zones:

Zone I is the section of the linear dependence of the pressure drop and contamination of the filter element, apparently corresponding to filtration with gradual clogging of the filter element pores by impurity particles [8, 9];

Zones II, III, and IV are the nonlinear section corresponding to filtration through partially clogged pores and sediment;

Zones III and IV are characterized by a high and nearly constant rate of increase in pressure drop as the filter element becomes contaminated. Zones I–III comprise the working portion of the check filter characteristic.

Contamination by the end of the linear zone I, according to the results of the experiments, amounts to 34–38% of the dirt capacity of the tested filter elements. Using only the linear zone when using a check filter limits its service life in terms of contaminant capacity by 2.5–3 times.

The resulting dependence (fig. 9) is similar to the results presented in [14].

The root-mean-square errors of measurements of the pressure drop and volume of the test liquid, calculated according to the authors' method [15], are given in Table 3.

Table 3

Measurement Errors

Name	Size	Value
Measurement of pressure drop across the filter element		
Root mean square of absolute deviations σ	kPa	2.61
3σ interval with confidence probability of 0.997	kPa	7.83
Maximum absolute deviation from the best (approximating) curve	kPa	7.36
Ratio of 3σ to the measurement range	%	3.13
Measurement of test fluid volume		
Root mean square of absolute deviations σ	l	0.694
3σ interval with confidence probability of 0.997	l	2.083
Maximum absolute deviation from the best (approximating) curve	l	1.409
Ratio of 3σ to the measurement range	%	1.23

Table 4

Instrumental measurement errors

Name	Size	Value
Absolute error of time measurement (t)	s	0.10
Absolute error of pollutant mass measurement (m)	g	0.01
Absolute error of test fluid temperature measurement (T)	°C	1.00
Basic absolute error of pressure measurement (Pf0)	kPa	0.38
Additional (temperature) absolute error of pressure measurement (PT)	kPa	0.11
Absolute error of pressure sensor: Pf = Pf0 + PT	kPa	0.49
Absolute error of level measurement (L)	mm	1.00
Absolute error of volume measurement (V)	l	0.20

Table 5

Computation Errors

Name	Size	Value
Pollutant concentration calculation error: mv = m/V	g/m^3	0.12
Filter element contamination calculation error with area S: mf = V(t) · mv/S	g/m^2	0.86
Test fluid flow rate calculation error: Q = dV(t)/dt	l/min	0.10

Instrumental measurement errors, determined using the authors' methodology[13], are shown in Table 4.

The errors in calculating the specific contaminant capacity and flow rate, determined according to [16], are shown in Table 5.

Note:

ρ – fuel density, kg/m^3;

Sf – filter element area, m^2;

mf – specific contaminant capacity of the filter element, g/m^2;

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[13] ZOND-20 Series Pressure Transducers (Sensors). (2017). Models K1, K2, K3, K4, K4I, K6, K7, K7I, K9, K10, K11: Operation Manual GKND.406233.008 RE. Part 1. Moscow: Gidrogazpribor, 65 p.

Mf – contaminant capacity of the filter element, g;

mv – average concentration of mechanical impurities in fuel, g/m^3;

Q – average fuel consumption through the filter element, m^3/s;

Q1 – average aircraft refueling rate, m^3/s;

T – service life of the check filter, hours;

R – the service life of the check filter, in thousands of tons of fuel loaded into the aircraft.

The contaminant capacity of the check filter can be expressed by the following relationships:

$$Mf = mf \cdot Sf = mv \cdot Q \cdot T \cdot 3600,$$

from which the resource of the check filter can be determined:

$$T = \frac{mf \quad Sf}{mv \quad Q \quad 3600} \tag{1}$$

and

$$R = 0{,}0036 \cdot Q1 \cdot \rho \cdot T. \tag{2}$$

From (1) and (2), it follows that the service life of the check filter can be increased by increasing its area and decreasing the flow rate through it.

Let us denote:

ΔP is the absolute measurement error of the pressure drop across the check filter, kPa;

Δm is the amount of mechanical impurities introduced per 1 m^2 of the check filter, g/m^2, when the pressure drop across it changes by ΔP (fig. 9);

Δt is the time interval, s, during which ΔP and Δm change;

mv1 is the rejection limit of aviation fuel contamination, g/m^3;

$\frac{\mathrm{dmf}}{\mathrm{dPf}}$ = Dmp is the derivative of the mf (Pf) curve (fig. 9);

ΔM is the amount of mechanical impurity supplied to the check filter, g, when the pressure drop across it changes by ΔP (fig. 9).

The amount of mechanical impurity supplied to the control film over time Δt can be expressed by the following relationships:

$$\Delta M = Dmp \cdot \Delta P \cdot Sf = Q \cdot \Delta t \cdot mv1, \tag{3}$$

from which the sensitivity of the check filter can be determined:

$$\Delta t = \frac{Dmp \quad \Delta P \quad Sf}{Q \quad mv1} \tag{4}$$

The sensitivity of the check filter is better, the shorter the time Δt. According to (4), the lower the error of the differential pressure sensor, the smaller the filtration area and the higher the flow rate through the check filter, the higher the sensitivity. It should be noted that the filtration area and flow rate have an opposite effect on the resource (1) and sensitivity (4) of the check filter.

Using the experimental dependence mf(Pf) (fig. 9) and formulae (1), (2), (4), a parametric study was conducted to select the best parameters for the check filter. Figure 10 shows the dependence of the sensitivity and check filter resource, using the studied filter elements. For clarity, the resource is expressed in the number of refills of the aircraft, with a volume of 15 m^3. Calculations for the graphs in Figures 10 and 11 were performed for an average flow rate through the check filter equal to 4 l/min; refilling rate of 1200 l/min; rejection level of 2 g/t and pressure sensor ZOND-20 code 73 with a scale of 2.5 kPa, basic error of 0.15%, for fuel temperature −40…+40 °C.

On a lightly contaminated filter element (zone I, fig. 9), the pressure drop changes relatively slowly when solids enter it. As the filter element becomes contaminated (zone II, fig. 9), the rate of pressure drop change increases, reaching maximum values in zone III. Accordingly, the response time of the check filter to the maximum contamination level decreases as the filter element becomes increasingly clogged.

For the studied filter elements, the optimal filtration area is (0.05…0.10) m², which is within the limits of existing production. The service life of the check filter will be 200…400 aircraft

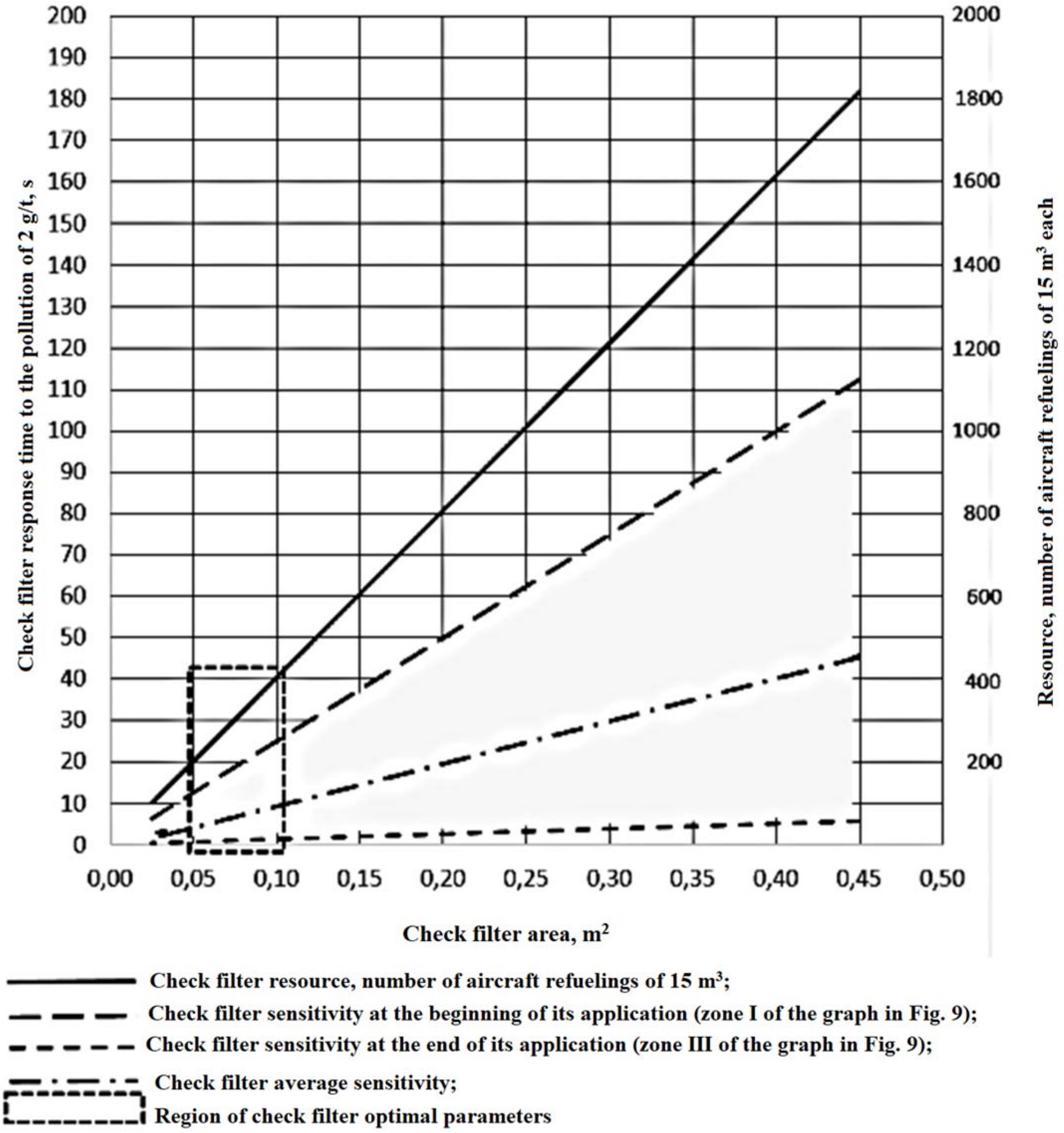

Fig. 10. Dependence of the check filter service life and sensitivity on the filtration area

refills with a volume of 15 m³ (2.35…4.70) thousand tons, and the response time to the maximum solids level will be no more than 25.0…12.5 s; on average, it will be 5…10 s.

Figure 11 shows the change in a parameter important for selecting a check filter – the number of switching operations of valves Kp2, Kp3, and Kp4 (fig. 3) during one "typical" refueling of 15 m³. For the studied filter element, valve switching will be required no more than once per refueling. It is desirable to automate this process.

An experimental study of the dependence of pressure drop across a filter element on the amount of solids supplied to it, along with calculations performed using the resulting relationship, demonstrated the feasibility of using a check filter for continuous monitoring of solids levels in aviation fuel. The optimal dimensions of the check filter and measuring instruments for continuous monitoring of jet fuel cleanliness based on the resource-sensitivity criterion were determined.

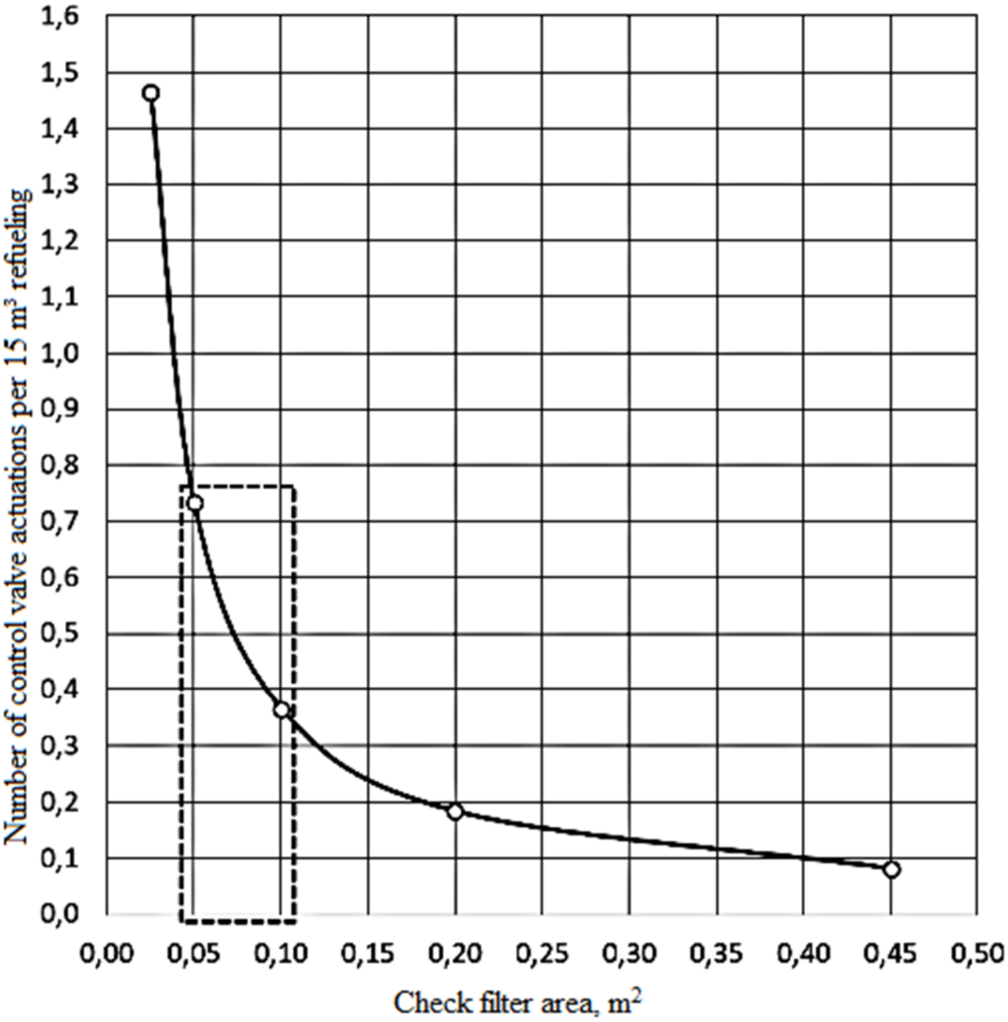

Fig. 11. Dependence of the number of valve (V) actuations on the filtration area

Conclusion

1. The effectiveness of using a partial-flow check filter for continuous monitoring of aviation fuel cleanliness during aircraft refueling has been proven.

2. The relationship between the pressure drop across the filter element and the mass of accumulated mechanical impurities has been established.

3. The optimal filter surface area of the check filter has been determined to be 0.05…0.10 m².

4. The proposed check filter design has been established to provide:

– a long service life of up to 200…400 refueling procedures;

– high sensitivity – contamination detection time is 5…10 seconds.

5. The feasibility of creating a system for operational monitoring of aviation fuel cleanliness using a check filter has been confirmed.

6. The results obtained can be used to develop new rapid methods for measuring the industrial cleanliness of aviation fuel and to upgrade existing ones. They can also serve as the basis for the development of new sensors and dynamic monitoring systems (continuous assessment) of aviation fuel cleanliness in the process chain of its preparation and refueling in aircraft.

7. Implementation of the developed solution and integration into existing automated process control systems will improve the automation of

refueling complex processes and, consequently, flight safety by preventing the refueling of aircraft with substandard fuel.

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