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The Prediction of Failure in the Gas Filtration System in Low-Pressure Carburising Furnaces

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Abstract
Predictive maintenance is one of the key aspects of Industry 4.0. The article presents the results of experimental tests of nitrogen purification filters in the installation of a low-pressure, metal processing device. The aim of the research was to develop a predictive algorithm for making decisions regarding the replacement of used filters, based on flow analysis and measurement of the pressure difference in front of and behind the tested filter. For the purposes of the research, a special test stand was constructed, which made it possible to determine the operating characteristics of three selected filters. Based on the tests carried out, the limit characteristics of the parameters measured were determined, identifying the need to replace filters in the gas installation.

Keywords
Predictive maintenance, industrial gas filters testing, process supervision, identification and control methods, maintenance models and services.

Introduction

The technology of metal heat treatment, including low-pressure carburising processes, is a key process that enables the improvement of the properties of products used in many industrial sectors, such as the automotive, aviation, energy, mechanical engineering and mining industries. The article presents research results enabling the prediction of failure states (filter clogging) of the nitrogen gas supply system, installed in a prototype, deep-hole device for low-pressure heat treatment. The heat treatment of metals, including low-pressure carburising requires the use of technical gases, which include nitrogen, acetylene and propane. Nitrogen is a highly desirable gas used in heat and thermo-chemical treatment of metals because it allows the required high parameters of the final products, such as reducing or eliminating surface oxidation, improving quality and increasing production efficiency to be obtained. The inert nature of this gas allows it to be used to protect most molten and heated metals during processing. Nitrogen is used in the following processes: atmospheric inerting, brazing, annealing, carburising/nitriding, hardening, sintering, cooling. Nitrogen, as used in heat treatment, should be characterised by a high purity class 4 or 5 (between 99.999 and 99.99%, i.e. the level of impurities from 10 to 100 ppm). One of the important elements of the gas system are gas filters in heat treatment devices, which enable the purification of compressed nitrogen from solid particles, moisture and oil aerosol.

Prediction of failure states in vacuum heat treatment furnaces is important because possible disturbances, occurring during the processing of products, may result in the charge being degraded, the value of which may exceed the value of the heat treatment device. Improper heat treatment of machine elements or components used in the automotive or aviation industry may result in large financial losses or a threat to human health and life (Kłos et al. 2021; Kłos et al., 2022). The article presents the results of experimental tests of nitrogen purification filters installed in the gas system of low-pressure metal heat treatment devices, in order to predict failure states (dysfunction of the filtering system due to filter clogging). A laboratory station and methodology for testing nitrogen system filters based on simulating emergency states was proposed.

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Literature review and outlining of the problem

Testing the filtering efficiency of technical gases is an important research area that is often used in areas such as the chemical industry, production, environmental protection and others. There are many scientific works, articles and literature sources that discuss various aspects related to the production and filtration of technical gases, such as industrial gas production, gas purification, filtration technology and filtration efficiency (Lin et al. 2019); Liu et al. 2018); Tanabe et al. 2011); Zhang et al., 2022). Research related to the development of technology for purifying industrial gases and air, covers the areas for designing high-performance filters, using new methods and materials (Kwon et al., 2021); Laguardia et al., 2017); Ptak, 2017). Bulejko et al. (2018) and determines filtration performance of polypropylene hollow-fibre membranes (HFMs) for removing submicron particles from air (Bulejko et al., 2018). An important area of research is the study of filter parameters. Filtration velocity, permeability, porosity, the pressure drop across the filter, the cleaning pulse interval, the baseline pressure drop, filtration efficiency and the durability of filters (Alonso-Fariñas et al., 2013) all belong to the main parameters studied. Research, on the impact of changing important parameters re- the optimization of filter performance, is carried out for various operating conditions, such as filtration speed, particle concentration, pressure and temperature (Lupión et al., 2010). Another example of testing the effectiveness of filtering technical gases is the use of fibrous ceramic filters for gas purification at high temperatures (Gong et al., 2022). Much of the research carried out involves the filtration of industrial gases produced on an industrial scale in order to obtain their high purity (Lin et al, 2019); Ourya et al., 2023). Comparative analysis of the depth of particle deposition in polypropylene, polyester and acrylic filters was the objective of research conducted by Tanabe et al. (2011). In order to analyse the efficiency of filter operation, numerical models of the flow and filtration characteristics of industrial gases are built, which are then verified, based on experimental tests (Yu et al. 2020).

The research results presented in this article concern the prediction of failure states in the gas system supplying nitrogen to the low-pressure heat treatment process in vacuum furnaces. Prediction of emergency states of resource failures is a key element of modern production systems based on the Industry 4.0 concept (Gouiaa-Mtibaa et al., 2018); Vu et al. 2021); Cao et al., 2022); Lakshmi and Kumar, 2022). For the purposes of the research, a laboratory station was built to analyse failure states of nitrogen filters used in low-pressure carburizing furnaces. The research stand created made it possible to simulate emergency states of the gas system (filter clogging) and develop an algorithm for predicting filter failure. Based on the analysis of the causes of the decrease in the flow rate of dosed process gases, two areas of problems with deterioration of the efficiency of the gas system were diagnosed. The first cause of the decline in the flow of process gases diagnosed, is the reduced flow of gases through the filter, which becomes contaminated as a result of operation and, as a result, the efficiency of the gas flow through it, is reduced. The second reason for reducing the efficiency of gas flow in the gas system results from the clogging of the collector nozzles supplying gas to the furnace chamber behind the mass valves. Based on the above analysis, it was decided that two analogue pressure sensors would be used to detect the reduction in gas flow through the filter. The first sensor $P1$ will be installed in front of the filter, the second sensor $P2$ will be installed behind the filter. Such a system for analogue sensors will allow measurements to be taken, using the $P1$ sensor, in order to monitor the pressure in the gas supply installation, while using the $P2$ sensor will allow the pressure *behind* the filter to be monitored, thus enabling the pressure difference to be determined ($\Delta P = P1 - P2$) by allowing the deterioration of the gas flow through the filter to be monitored. In order to monitor the reduction in flow at the collector nozzles, it was proposed to use a mass valve with extensive control and diagnostic functions.

Model of the gas system

The diagram of the gas system used to test the decrease in the flow of process gases supplied to the furnace chamber is shown in Fig. 1. The system presented consists of:

- a 200 bar nitrogen cylinder
- a pressure reducer mounted on the cylinder (reducing the pressure to 8 bar)
- a pressure reducer with a smaller range (reducing the pressure to 1,5 bar)
- a gas filter
- a nitrogen mass valve: Voegtlin GSC-C9SA-BB12
- a $P1$ analogue sensor measuring gas pressure in front of the filter: IFM PQ3834
- a $P2$ analogue sensor measuring gas pressure behind the filter: IFM PQ3834
- a $P3$ analogue sensor measuring gas pressure between reducers: IFM PT5404

- a $D1$ throttle valve placed in front of the filter (to simulate flow disruption on the filter)
- a $D2$ throttle valve placed behind the mass valve (to simulate flow disruption on the nozzles)

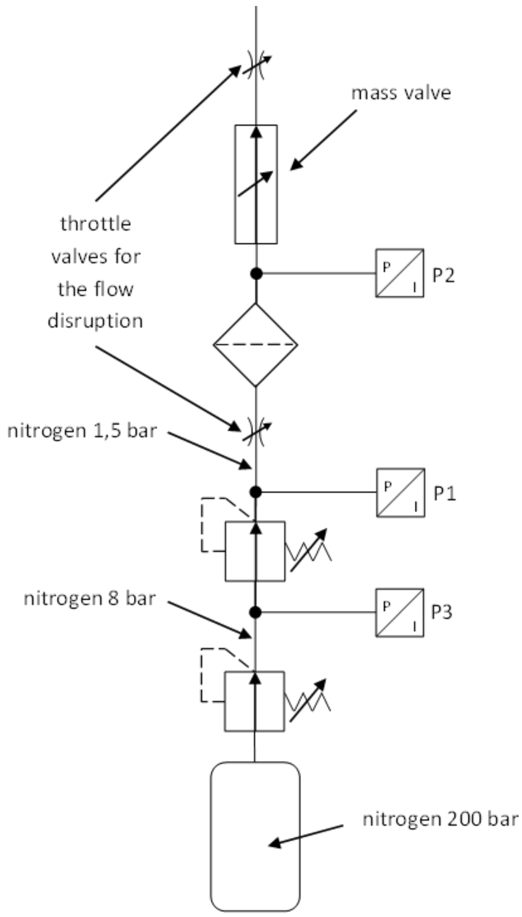
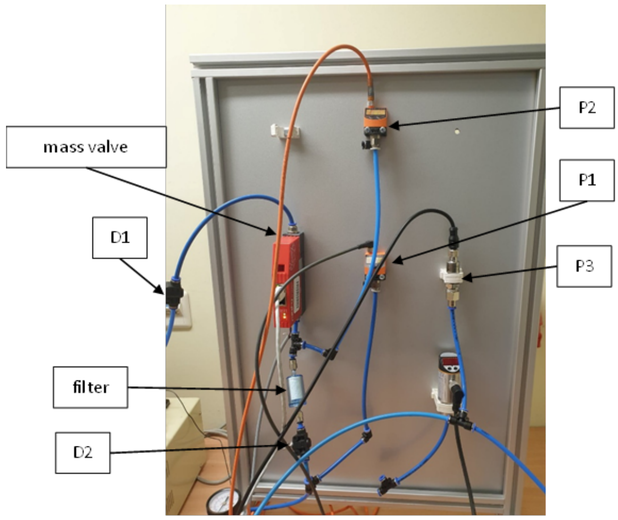


Fig. 1. Diagram of the gas filter testing

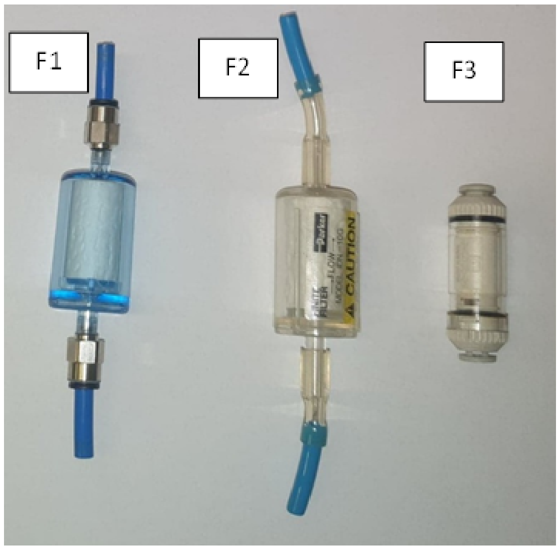
The Siemens S7-1516 PLC controller with input/output modules was used to control the mass valve digital analogue and as well as the HMI screen. The ProfiNet communication protocol was used to communicate with the mass valve, allowing the mass valve and diagnostics to be extensively controlled. Fig. 2 shows a laboratory station created for testing filters for a nitrogen gas system and 3 filters that were the subject of the research experiments.

Results of the experimental research

During the tests, steps were first taken to monitor the gas flow through the filter. For this purpose, the choke behind the mass valve and the throttle valve in front of the filter were unscrewed so that neither posed any resistance to the flowing gas; the flow resistance characteristics of the new filter were then established. Three different filters from different manufacturers were used for the tests, shown in Fig. 2b. The filters used are: Filter F1 – Filter incl. Fitting 6 mm; F2 – Parker IDN – 10G; F3 – SMC ZFC100-06. F1 filters were brand new, F2 and F3 filters were used for approximately 20 hours of operation.



(a)



(b)

Fig. 2. Laboratory test station a) and tested filters b)

Tables 1, 2 and 3 present the results of experimental tests carried out for individual filters. The data determines the set and measured gas flow value (V), pressure in front of and behind the filter ($P1, P2$) and the pressure difference (ΔP). The set and measured gas flow (V) are given in ln (liter normal).

Table 1
Test results of for filter F1

Set V [ln]	measured V [ln]	ΔV [ln]	$P1$ [bar]	$P2$ [bar]	ΔP [bar]
0	0	0	1.57	1.57	0.000
1	1	0	1.45	1.45	0.000
2	2	0	1.44	1.44	0.000
3	3	0	1.44	1.44	0.000
4	4	0	1.43	1.43	0.000
5	5	0	1.42	1.42	0.000
6	6	0	1.41	1.41	0.000
7	7	0	1.41	1.40	0.010
8	8	0	1.406	1.392	0.014
9	9	0	1.393	1.377	0.016
10	10	0	1.390	1.372	0.018
11	11	0	1.382	1.357	0.025
12	12	0	1.378	1.348	0.03
13	13	0	1.376	1.341	0.035
14	14	0	1.370	1.327	0.043
15	15	0	1.360	1.313	0.047

Table 2
Test results for filter F2

Set V [ln]	measured V [ln]	ΔV [ln]	$P1$ [bar]	$P2$ [bar]	ΔP [bar]
0	0	0	1.57	1.57	0.000
1	1	0	1.45	1.45	0.000
2	2	0	1.44	1.44	0.000
3	3	0	1.43	1.43	0.000
4	4	0	1.42	1.42	0.000
5	5	0	1.417	1.417	0.000
6	6	0	1.41	1.41	0.000
7	7	0	1.40	1.39	0.010
8	8	0	1.395	1.385	0.010
9	9	0	1.39	1.377	0.013
10	10	0	1.381	1.367	0.014
11	11	0	1.374	1.354	0.020
12	12	0	1.368	1.34	0.028
13	13	0	1.368	1.333	0.035
14	14	0	1.36	1.32	0.040
15	15	0	1.356	1.31	0.046

Table 3
Test results for filter F3

Set V [ln]	measured V [ln]	ΔV [ln]	$P1$ [bar]	$P2$ [bar]	ΔP [bar]
0	0	0	1.57	1.57	0.000
1	1	0	1.44	1.44	0.000
2	2	0	1.43	1.43	0.000
3	3	0	1.42	1.42	0.000
4	4	0	1.41	1.41	0.000
5	5	0	1.41	1.41	0.000
6	6	0	1.4	1.4	0.000
7	7	0	1.39	1.38	0.010
8	8	0	1.39	1.38	0.010
9	9	0	1.38	1.37	0.010
10	10	0	1.378	1.364	0.014
11	11	0	1.371	1.351	0.020
12	12	0	1.37	1.345	0.025
13	13	0	1.364	1.334	0.030
14	14	0	1.354	1.317	0.037
15	15	0	1.351	1.311	0.040

In order to determine the characteristics of individual filters. the flow was set from 0 ln to 15 ln (15 ln is the maximum flow for the mass valve used) for each one and the actual flow and pressures $P1$ and $P2$ were measured. Based on the parameters measured. the flow difference and pressure difference were determined. In Fig. 3 the characteristics of the pressure ratios in front of and behind ($P1$) ($P2$) the various flows are presented.

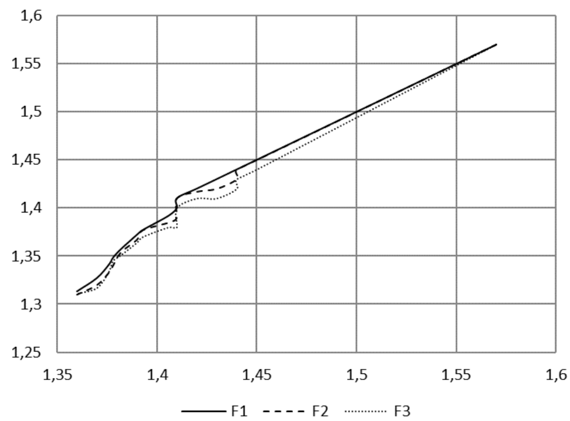


Fig. 3. Characteristics of the values indicated by sensors $P2$ to $P1$ for individual filters

In Figure 4 the characteristics of the pressure difference relative to the set flow are presented. both graphs present the combined characteristics for the three filters tested F1. F2 and F3.In analysing the measurement data and characteristic curves, it was found that all three filters have a similar resistance to gas flow in relation to the given gas flow, therefore only one F1 filter, which is a brand-new filter, was selected for further tests.

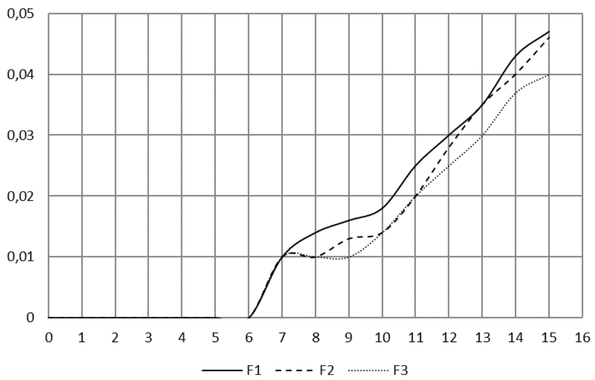


Fig. 4. Characteristics of the pressure difference relative to the set flow for three filters

An important aspect of the research was the answer to the question as to what the characteristics of individual filters for different pressure values of the flowing gas are.

Therefore, in the next stage in testing the F1 filter was selected to examine the ΔP resistance to the flowing gas at various set speeds for three pressures, supplying the mass valve. The test was carried out for three supply pressures of 1.57 bar, 1.05 bar and 0.54 bar set on the reducer. The results of research are summarised in Tables 4, 5 and 6 (characteristics of the pressure difference for the F1 filter, in relation to the set flow for three supply pressures).

In the next step, a test was carried out consisting in setting the flow from 1 ln to 15 ln with a step of 5 ln and setting the choke located in front of the filter so as to limit the actual flow to a level of 0.1 ln below the set flow.

The research conducted shows that for the highest set flow of 15 ln, the pressure difference was approximately 0.86 bar. Increasing the damping on the filter resulted in an increase in the difference between the actual flow and the set one and an increase in the pressure difference in front of and behind the filter. Due to the above, it was assumed that to ensure undisturbed gas flow through the filter, the pressure difference ΔP should not exceed 0.8 bar. This value will ensure free

Table 4
Measurement results for F1 filter parameters for a pressure of 1.57 bar

Set V [ln]	measured V [ln]	ΔV [ln]	$P1$ [bar]	$P2$ [bar]	ΔP [bar]
0	0	0	1.57	1.57	0.00
1	1	0	1.45	1.45	0.00
2	2	0	1.44	1.44	0.00
3	3	0	1.44	1.44	0.00
4	4	0	1.43	1.43	0.00
5	5	0	1.42	1.42	0.00
6	6	0	1.41	1.41	0.00
7	7	0	1.41	1.40	0.010
8	8	0	1.406	1.392	0.014
9	9	0	1.393	1.377	0.016
10	10	0	1.39	1.372	0.018
11	11	0	1.382	1.357	0.025
12	12	0	1.378	1.348	0.030
13	13	0	1.376	1.341	0.035
14	14	0	1.37	1.327	0.043
15	15	0	1.36	1.313	0.047

Table 5
Measurement results of F2 filter parameters for a pressure of 1.05 bar

Set V [ln]	measured V [ln]	ΔV [ln]	$P1$ [bar]	$P2$ [bar]	ΔP [bar]
0	0	0	1.05	1.05	0.00
1	1	0	0.94	0.94	0.00
2	2	0	0.935	0.935	0.00
3	3	0	0.927	0.927	0.00
4	4	0	0.922	0.922	0.00
5	5	0	0.918	0.918	0.00
6	6	0	0.911	0.911	0.00
7	7	0	0.907	0.895	0.012
8	8	0	0.901	0.887	0.014
9	9	0	0.897	0.877	0.020
10	10	0	0.889	0.864	0.025
11	11	0	0.882	0.851	0.031
12	12	0	0.879	0.838	0.041
13	13	0	0.872	0.826	0.046
14	14	0	0.866	0.813	0.053
15	15	0	0.86	0.796	0.064

Table 6
Measurement results of F1 filter parameters for a pressure of 0.54 bar

Set V [ln]	measured V [ln]	ΔV [ln]	$P1$ [bar]	$P2$ [bar]	ΔP [bar]
0	0	0	0.54	0.54	0.00
1	1	0	0.433	0.433	0.00
2	2	0	0.424	0.424	0.00
3	3	0	0.416	0.416	0.00
4	4	0	0.407	0.407	0.00
5	5	0	0.404	0.397	0.007
6	6	0	0.395	0.381	0.014
7	7	0	0.39	0.373	0.017
8	8	0	0.384	0.361	0.023
9	9	0	0.377	0.35	0.027
10	10	0	0.37	0.333	0.037
11	11	0	0.364	0.319	0.045
12	12	0	0.358	0.303	0.055
13	13	0	0.351	0.285	0.066
14	14	0	0.342	0.261	0.081
15	15	0	0.342	0.252	0.09

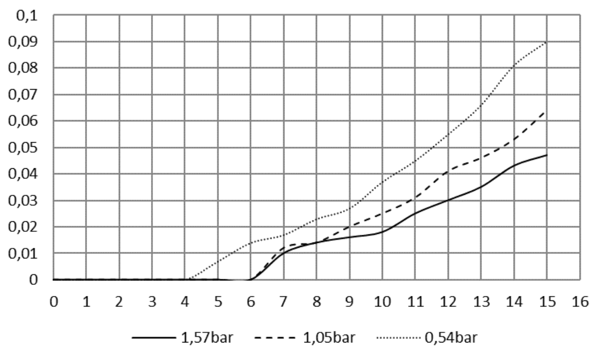


Fig. 5. Characteristics of the pressure difference for the F1 filter in relation to the set flow for three supply pressures

flow in the entire range of set flows. Values for zero flow are omitted from the charts. The values are included in the table, in order to check the pressure on the supply side of the system before activation of the mass valve.

Prediction algorithm for the replacement of technical gas filters

To develop an algorithm for detecting clogging in technical gas filters, it is recommended to adopt the same constant pressure difference in front of and behind the filter at the level of 0.8 bar. However, such an algorithm does not take into account the actual characteristics of filter contamination and causes that at lower set gas flows, the algorithm will respond with a filter replacement alarm if the filter contamination is lower than permissible. Based on the research conducted, it was decided to develop an algorithm based on the actual characteristics, taking into account the relationship between the pressure difference and the set flow. Below, is the equation that determines the trend line for the recommended pressure difference upstream and downstream of the filter.

$$\Delta P_{\text{algo}} = -0,0429 \cdot \Delta P + 1.4429 \qquad (1)$$

Algorithms for monitoring the filter contamination state, which are based on the characteristics described in equation (1), were recommended for testing the effectiveness in predicting failure. In order to verify it, pressure differences $P1$ and $P2$ were tested for various set gas flow rates for filters with simulated contamination levels. The symbols Z1, Z2, Z3 and Z4 mark filters with various degrees of simulated contamination, where the Z1 filter did not cause any flow throttling, while Z4 caused the greatest throttling to it. In Fig. 6, the characteristics of the pressure difference, depending on the gas flow rate for four simulated filter contaminants are summarised. Only the Z1 filter, on which flow throttling was not set (contamination simulation), operated correctly throughout the entire range without causing a drop in the flow rate at the mass valve. Filter Z2, with simulated contamination greater than Z1 did not cause any throttling of the flow rate measured V to set $V = 5$ ln. The Z2 filter in the range from 10 ln to about 12 ln also did not cause a decrease in the flow rate measured V, but, after exceeding about 12 ln, this filter caused an increase

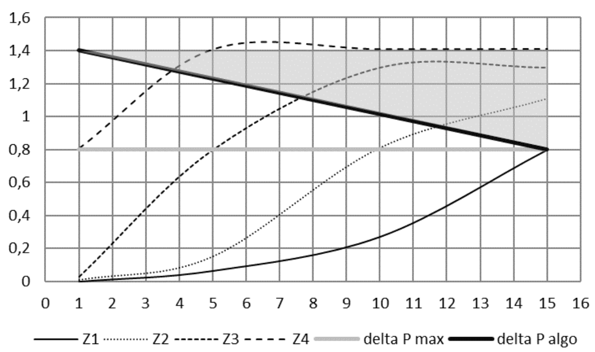


Fig. 6. Comparative characteristics of filters with different degrees of contamination

in the delta V value, which causes a decrease in the flow efficiency through the mass valve. The Z3 filter did not cause a drop in the flow rate measured by the mass valve to approximately 7,5 ln.

Behind this value, an increase in delta V caused a decrease in the efficiency of the flow rate through the mass valve. The last filter with the highest throttling, *q.v.*, set Z4 worked from the beginning set $V = 1$ ln above the range adopted in the first algorithm with a constant ΔP max value, while in the range set V from 1 ln to approximately 4 ln the filter did not cause any disruption in the flow rate through the mass valve. Only above set 4 ln, did the Z4 filter increase the ΔV value, which resulted in a reduction in the efficiency of the gas flow rate through the mass valve. As can be seen in Fig. 6, the ΔP algorithm increases the operating range of filters with higher contamination, but only to a limited extent. Thanks to this algorithm, the system will report a filter failure when it is more contaminated, but only within a limited range of the set gas flow rate set V. If the system is to operate correctly in the entire operating range of the mass valve from 0 ln to 15 ln, the pressure difference ΔP cannot be greater than 0.8 bar.

In the next step, tests to assess disruptions in the actual flow of process gases behind the mass valve on the nozzles of the collector supplying gases to the furnace chamber are conducted. At the stage of analysis of this flow disruption, it was found that, as a result of the operation of the furnace chamber, permanent impurities are created, reducing the cross-section of the gas supply nozzles. This disruption causes an incorrect course of the technological process performed in the furnace chamber. Due to the above, an adjustable flow choke was installed behind the mass valve and used to simulate a disturbance in the reduction of the flow of process gases behind the mass valve. Due to the use of a mass valve in the tests, which allows advanced control of the mass valve *via* the ProfiNet bus, the tests used the ability to read the actual flow from the valve in real time. This parameter allows analysis of the actual flow regulated by the mass valve in relation to the set flow and assessment of the disturbance. The algorithm can be based on a constant value of the difference between the actual and the set flow (e.g. 0.5 ln) or on a percentage difference of these values (e.g. 10% of the set value). An algorithm was used to calculate the difference in the actual flow rate V. Measured relative to the set rate, the flow rate V was set at the level of 10%; when this value is exceeded, the algorithm reports an error suggesting that the nozzle cleaning procedure be performed behind the collector.

Conclusions

In the article are presented the research results on the basis of which a predictive algorithm was developed to support the identification of the level of wear (clogging) of filters used for nitrogen purification in low-pressure gas installations for the heat treatment of metals. The research was carried out based on a constructed laboratory station according to the following methodology:

1. Determination of the operating characteristics of the filters tested (measurement of pressure in front of and behind the filter for various gas flow values).
2. Determination of filter operating characteristics for various gas pressure values in the installation.
3. Determination of the recommended differential pressure threshold, taking into account the set flow (limit threshold for filter replacement) based on specific characteristics.
4. Verification of the algorithm's operation by simulating filter wear as a result of throttling the gas flow.
5. Implementation of the algorithm in the nitrogen flow monitoring system.

Both the proposed laboratory stand and the methodology of the conducted energy tests can be implemented to test filters used in installations of other technical gases, such as acetylene and argon, in technological installations of other devices. The key to the functioning of the predictive system supporting filter replacement is determining the characteristics for a given filter and measuring the gas flow and pressure differences in front of and behind the filter. Further research will be carried out for other types of technical gases and other ranges of gas flow and pressure.

Acknowledgments

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