Identification of Flow Structure in Centrifugal Machines

M. I. Filimonov[1,2]([✉]), A. E. Novikov[1,2], and M. I. Lamskova[2]

[1] All-Russian Research Institute of Irrigated Agriculture, 9, St. Timiryazev, Volgograd 400002, Russia
`maksim.filimonov.work@yandex.ru`

[2] Volgograd State Technical University, 28, Prospect Them. Lenin, Volgograd 400005, Russia

Abstract. High rates of world industrialization and intensive development of various economic sectors have led to extensive pollution of waters by domestic, industrial and agricultural wastewater. In 2018, as in Russia more than 40,000 million m^3 of wastewater were generated as a result of anthropogenic activities, of which only 10% were properly treated, 60% were discharged with excess pollutants and 30% of the wastewater were not treated at all, leading to increased environmental stress in places for their disposal. The disastrous situation of the national heterogeneous liquid-phase wastes treatment industry is explained by the low efficiency of technologies providing the decrease in the concentration of dispersed phase polluting components to standard values. One of the most promising methods of wastewater treatment is the centrifugation. However, the complexity of selecting the construction and the optimal technological mode prevents the widespread distribution of this technology. The hydrodynamic flow structure in the rotor of the filter machine has been studied in order to predict the separation capacity of centrifuges. The formalization of the flow particle motion in a centrifugal field has allowed us to establish that its hydrodynamics is described by a mathematical model of sequentially connected zones of mixing unequal volume.

Keywords: Centrifugal separation · Filtering centrifuge · Hydrodynamic flow structure · Response curves · Heterogeneous liquid-phase system

1 Introduction

During recent years, the problem of water objects pollution of by industrial waste generated by various sectors of the national economy and industry has become particularly relevant in Russia. According to the report of the Ministry of Natural Resources of the Russian Federation [1] in 2018, the total water intake was 68,033 million m^3, while the volume of wastewater (WW) exceeded 40,000 million m^3, of which only 10% were properly treated, 60% were discharged with excess of polluting components and 30% of wastewater were not subjected to any treatment at all [2]. Such impressive figures can be explained by the lack of a comprehensive approach aimed at reducing the volume of waste disposal by involving WW in the recycling system. China is the world leader in processing and recycling of liquid-phase waste, and its treatment facilities ensure the

regeneration of 60% of accumulated wastewater [3]. It should be noted that bioenergy technologies are successfully used in Latin America and the Caribbean that allow processing approximately 20% of the total volume of generated effluents every year [4]. In the USA, the technical equipment of water treatment systems is focused on the secondary use of water resources that ensure the return of 15% of the purified liquid used in recycling water supply lines or agricultural irrigation [5]. In Russia, this trend has not developed since the 50 s of the XX century, what has led to increased environmental tension of water ecosystems. As a result, no more than 7% of industrial and domestic wastewater is properly treated today [6, 7]. A barrier to the creation of national closed-cycle water systems is the low efficiency of the technologies reducing the polluting components in the liquid phase to standard values [8]. The world experience in preparing WW for recycling shows that the solution to the problem of liquid-phase waste disposal is in the complex processing, which is based on the stage of mechanical impurities separation, including removal sand and suspended solids. As a rule, the removal of coarse impurities and suspended particles is carried out in primary clarifier. However, these apparatus are characterized by low separation capacity due to small motive power, as well as they have large dimensions, leading to the need for large production areas. An alternative to clarifiers is rotary-type machines–centrifuges providing a high intensity of heterogeneous liquid-phase system separation in the field of centrifugal forces in combination with small equipment dimensions. Today, centrifuges are manufactured in two types: with a perforated rotor covered with a porous material or equipped with a metal mesh for centrifugal filtration and with a solid rotor for centrifugal deposition [9]. Taking into account the mechanical inclusions' size and concentration in wastewater, it is advisable to process them in filter centrifuges, since these machines allow to adjust the size of the separated particles by installing different filter material. The unavailability reliable description of the hydrodynamic flow of the heterogeneous stream in the centrifuge rotor prevents the widespread use of centrifugal wastewater filtration. Identification of the flow structure let to establish a model of the particle behavior in the centrifugal field and, as a result, optimize the construction parameters of filter centrifuges under different technological conditions.

2 Materials and Methods

The separation of heterogeneous liquid-phase systems in rotary-type filter machines is associated with an intense mechanical impact on solid particles caused by pulsations of the processed liquid passing through wall of the perforated rotor and filter material. The mechanism and specificity of the centrifuges' operation largely depend on the construction, but the main hydrodynamic dependencies are valid for all model range of rotary machines. The flow structure determines the nature of the dispersed component movement. The flow structure has been studied by a graphoanalytic method, based on comparing experimental response curves with known hydrodynamic models. Three most suitable typical flow structures have been established by the analysis of existing models (Fig. 1).
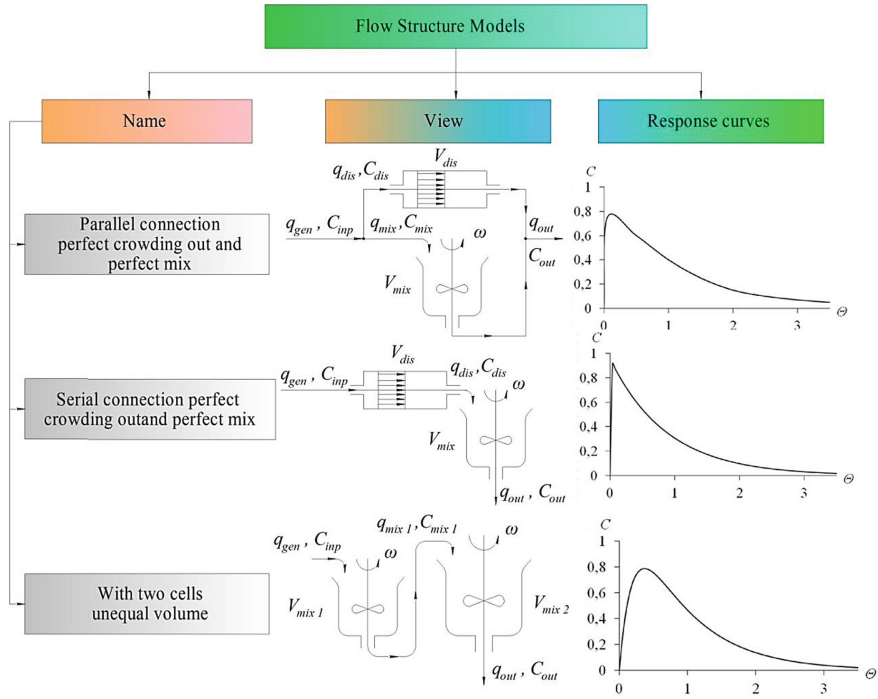
Fig. 1 A mathematical model describing the typical flow structures [10]: q_{gen}—total flow rate at the inlet; q_{dis}—flow rate in the ideal displacement zone; $q_{mix\ i}$—flow rate in the ideal mixing zone; q_{out}—flow rate at the exit; C_{inp}—indicator concentration at the input; C_{dis}—indicator concentration in the area of ideal displacement; $C_{mix\ i}$—indicator concentration in the area of ideal mixing; C_{out}—indicator concentration at the output; V_{dis}—volume of ideal displacement cell; $V_{mix\ i}$—volume of ideal mixing cell

The mathematical model of parallel connection of ideal mixing zones and ideal displacement zones is a complex combined model and described by a system of equations:

$$\begin{cases} C = \dfrac{(1-\alpha)^2}{1-\beta}\exp\left[-\dfrac{(1-\alpha)}{(1-\beta)}\Theta\right]; \Theta \neq \dfrac{\beta}{\alpha} \\ C == \dfrac{(1-\alpha)^2}{1-\beta}\exp\left[-\dfrac{(1-\alpha)\beta}{(1-\beta)\alpha}\right] + C_{in}\alpha; \Theta \neq \dfrac{\beta}{\alpha} \end{cases} \tag{1}$$

where β—ratio of displacement zone volume to total volume, $\beta = V_{in}/V$; α—ratio of flow rates, $\alpha = q_{in}/q$.

Considering the model of sequentially connected ideal displacement and ideal mixing zones, the total volume of the object was determined by the dependence:

$$V = V_{dis} + V_{mix} \tag{2}$$

For the case when zones are connected sequentially, the indicator concentration change is described by the equation:

$$C = \frac{1}{1-\beta} \exp\left[-\frac{(\Theta - \beta)}{(1-\beta)}\right], \Theta \geq \Theta_{in}. \tag{3}$$

The mathematical description of the flow structure for cell model consisting of two consecutive unequal volume cells has the following form:

$$C = \frac{1}{2\beta - 1}\left[\exp\left(-\frac{\Theta}{\beta}\right) - \exp\left(-\frac{\Theta}{1-\beta}\right)\right], \tag{4}$$

where β—volume part of the first cell:

$$\beta = \frac{1 + \sqrt{2\sigma^2 - 1}}{2}, \tag{5}$$

where σ^2—variance of the response curve, $\sigma^2 > 0.5$.

3 Results and Discussion

The research of the flow structure is based on the analysis of response curves obtained at the output of the object after creating an input perturbation [10, 11]. This method involves inserting a special tracer into the centrifuge by one of the standard methods with further tracking of changes in its concentration at the output. In chemical cybernetics, a pulse feed of a concentrated salt solution is used, at that solution electrical conductivity differs from that of the main stream [12, 13]. In this case, the concentration of the indicator at the exit of the machine is registered by a conductometric cell.

Developed experimental setup includes a filter centrifuge with a vertically mounted rotor 1, a centrifugal pump 2, tanks of the initial suspension 3 and filtrate 4, a conductometric cell 5, as well as shut off and control valves and instrumentation (Fig. 2) [14].

In [15], procedure of laboratory experiments is described in detail, and response curves have been obtained in a filter centrifuge in various technological modes as a result of experiments. To formalize the flow hydrodynamic structure, we have used the values of the concentration change over time at the rotor speed $n = 750$ rpm, which corresponds to the normal mode of operation of the device. Figure 3 shows a graphical interpretation of the indicator concentration change when the experiment is repeated thrice.

Substituting the experimental values of the indicator concentration change in the mathematical description of the models, we have obtained the results shown in Fig. 4.

Identification of the flow structure has been performed by the nonlinear correlation coefficient, which is characterized by a dependence:

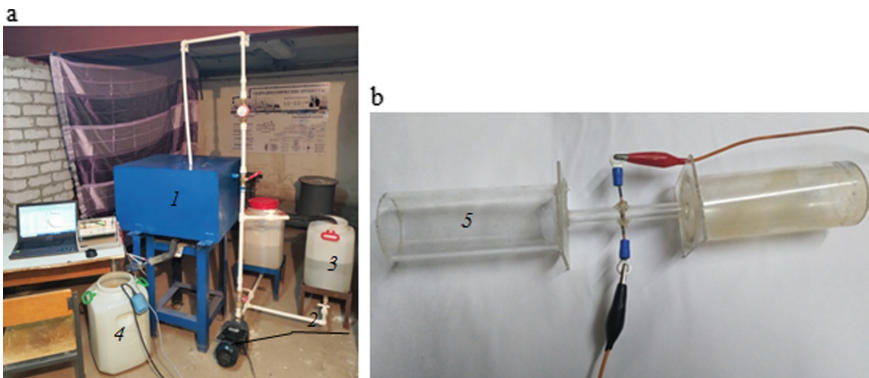$$R_{C\Theta} = \sqrt{1 - \frac{\sum (C_{ex} - C_t)^2}{\sum (C_{ex} - C_m)^2}}, \tag{6}$$

Fig. 2 Used laboratory equipment (position in the text). **a** Experimental setup. **b** Conductometric cell
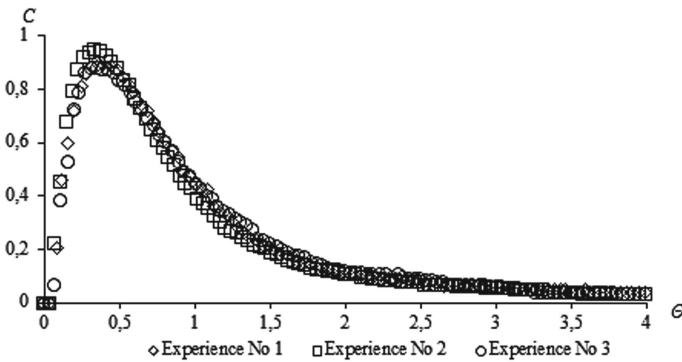

Fig. 3 Response curves in a filter centrifuge at $n = 750$ rpm

where C_{ex}—experimental values of the indicator concentration change; C_t—mathematical values of concentration changes for each model; C_m—average value of the experimental concentrations.

Relative $\delta_{(i)}$ and average relative $\bar{\delta}$ errors have been calculated using the following formulas:

$$\delta_{(i)} = \frac{C_{(i)} - C_{(i-1)}}{C_{(i-1)}} \cdot 100\%; \tag{7}$$

$$\bar{\delta} = \frac{\sum_{i=1}^{m} |\delta_{(i)}|}{m}. \tag{8}$$

Substituting experimental and theoretical values of changes in the indicator concentration in formulas (7) and (8), we have obtained the values of the correlation coefficient and the average relative error for each model. Obtained values are summarized in Table 1.
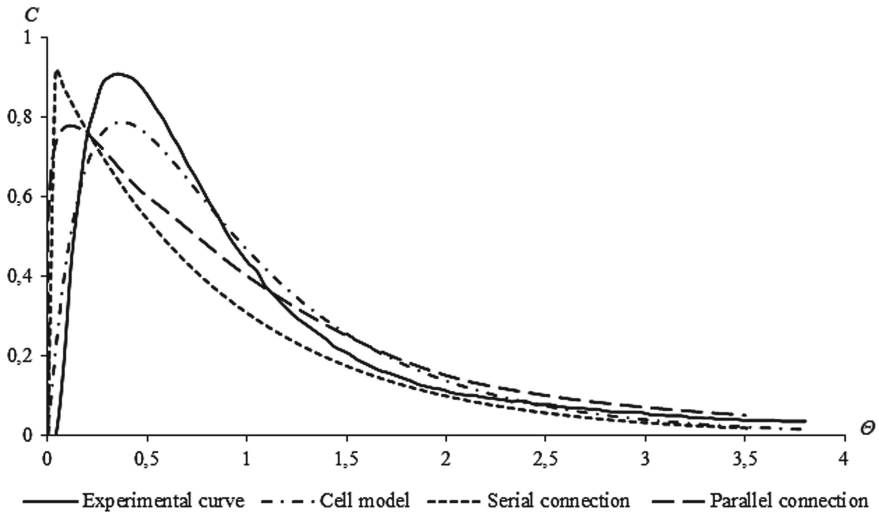
Fig. 4 Comparison of the experimental response curve with model graphs

Table 1 Results of identification of the flow structure in the filter centrifuge

Name of the mathematical model	Value of the correlation coefficient, R	Average relative error, $\bar{\delta}$ (%)
Model of parallel connection of ideal displacement and ideal mixing	0.72	9.0
Model of consecutive connection of ideal displacement and ideal mixing	0.78	8.7
Model of consecutive connection of two unequal volume cells	0.98	4.5

4 Conclusions

By analyzing the obtained values of the correlation coefficient and the average error, it has been found that the most tightness of the connection $R = 0.98$ and the minimum error $= 4.5\%$ is typical for a model with two consecutive unequal volume cells. In this regard, we can conclude that the hydrodynamic structure of the flow in the filter centrifuge is described by a cell model.

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