Досліджено вплив різних факторів на загальну ефективність вловлювання твердих часток у відцентрованому фільтрі нової конструкції із системою каналів із замкненими контурами. У процесі оброблення експериментальних даних запропоновано використати математичний підхід у вигляді апроксимації з метою отримання математичних залежностей оцінювання загальної ефективності вловлювання твердих часток різноманітних матеріалів. Отримані залежності доцільно застосовувати як при проектуванні, так і прогнозуванні роботи відцентрових фільтрів, а також автоматизації процесу

Ключові слова: ефективність, відцентровий фільтр, апроксимація, вловлювання часток, пилогазовий потік, сепараційна камера

Исследовано влияние различных факторов на общую эффективность улавливания твердых частиц в центробежном фильтре с системой каналов с замкнутыми контурами. В процессе обработки экспериментальных данных предложено использовать математический подход в виде аппроксимации с целью получения математических зависимостей оценки общей эффективности улавливания твердых частиц разнообразных материалов. Полученные зависимости целесообразно использовать как при проектировании, так и прогнозировании работы центробежных фильтров, а также автоматизации процесса

Ключевые слова: эффективность, центробежный фильтр, аппроксимация, улавливание частиц, пылегазовый поток, сепарационная камера

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ANALYSIS OF THE EFFICIENCY OF PURIFICATION OF GAS FLOWS IN A CENTRIFUGAL FILTER

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1. Introduction

Operation improvement and development of waste-free closed-circuit cycles remain the main ways to reduce dust emissions in the atmosphere. However, in those, still numerous, cases where these problems cannot be solved, the most effective and cost-saving means of cleaning of air and gases from dust before release into the atmosphere should be applied.

The fact that Ukraine has adopted the Directive 2001/80/ EU “On the limitation of emissions of certain pollutants into the air from large combustion plants” for the air protection from pollutants induces the reduction of particulate matter emissions in the environment to the level of 50mg·m^3/h in many industrial processes.

Various dust-collecting devices with individual characteristics are used to solve the above problems. The most important, which basically dictate their choice is the dust collection efficiency and aerodynamic drag, which determine the cleaning quality and energy consumption to achieve it.

Creation of more efficient dust-collecting equipment and development of the efficiency calculation methods is the urgent problem today.

2. Literature review and problem statement

Cyclone dust collectors, based on the action of the centrifugal force are used in many industries as the first stage of cleaning of process gases from particulate matter [1, 2].

Hundreds of designs and thousands of modifications have been developed in recent years. However, a sharp decline in the efficiency of cleaning of gas flows from particulate matter in these devices [3] does not allow using them as the only stage of cleaning in systems with high initial dust. High-efficiency cleaning of gas flow from particulate matter can be achieved by combining two cleaning principles in one device: centrifugal separation and multiple filtration through a self-regenerating dynamic dust layer. Combination of these processes is implemented in the centrifugal filter [4, 5].

It should also be noted that to date there is no full and accurate method for calculating the dust collection efficiency of cyclone dust collectors, which would consider all the structural features of the devices and processes occurring in them. Currently, there are several approaches to evaluating the efficiency of cleaning in cyclones. Known methods for calculating cyclones [6], based on the use of empirical probability functions, describing the parameters of the fractional efficiency of cyclone dust collectors and disperse structure of many types of industrial dust, are not accurate enough. This is caused by many factors. The most difficult-determined factor is the quantitative assessment of the impact of transition to a widespread application of a different dimension-type of the cyclone and changes in process parameters on the dust collection efficiency.

In the method [7], an attempt is made to consider the features of flows in the device, wall friction, multifractionality and input concentration of solids on the characteristics of the particulate collection in cyclone devices. The work [8] proposes a statistical correlation for evaluating fractional efficiency, which is satisfactory agreed with experimental data for cyclones of different geometry.

Thus, the inefficiency of cleaning of gas flows from particulate matter in existing dust collectors necessitates research in this area, that is the creation of a new design of the centrifugal filter, and at the same time leads to the development of mathematical tools for processing experimental data, both for research and development of design techniques.

3. Research goal and objectives

The research is aimed at developing mathematical approaches to evaluating the collection efficiency of particulate matter of different materials by the eight-channel centrifugal filter of a new design [9, 10], which will allow establishing a functional relationship between the collection efficiency of particulates and their diameters for different materials.

To achieve this goal, the following tasks are solved:

– study of the efficiency of the centrifugal filter using the laboratory test bench;

– analysis of the experimental data and development of a mathematical approach for constructing functional relationships between the collection efficiency of particulates and their diameters.

4. Research materials and methods for evaluating the collection efficiency of particulates of different materials

4. 1. Description of laboratory test bench

Centrifugal filters with a system of closed-circuit channels are widespread in different industries [11]. Centrifugal filters are based on the system of series-connected curvilinear channels with equal angles of rotation and cross-sectional areas. The channels are formed by two flat walls and cylindrical half shells of different curvatures. The closed circuit occurs in two adjacent channels in the presence of eccentricity between the axes of rotation of odd and even half shells.

For the aerodynamic testing of the centrifugal filter, the laboratory test bench was mounted in the laboratory of the Institute of Engineering Thermophysics, NAS of Ukraine, Department of Thermal Processes in Boilers (Fig. 1).

Operation of the laboratory setup was as follows: the centrifugal fan 5 was turned on for testing, the material was supplied by the screw feeder 9. The material supplied to the feeder was delivered to the measuring flue 1, where it was mixed with air. The resulting dust-gas flow was fed into the centrifugal filter 2, where the particulate matter was collected in the system of channels and distributed among isolated bins, connected to the pairs of the system channels, and cleaned gas flow got into the environment through the flue 3 and centrifugal fan 5. The laboratory setup operated under vacuum that was created by the centrifugal fan.

The eight-channel centrifugal filter is shown in Fig. 2.

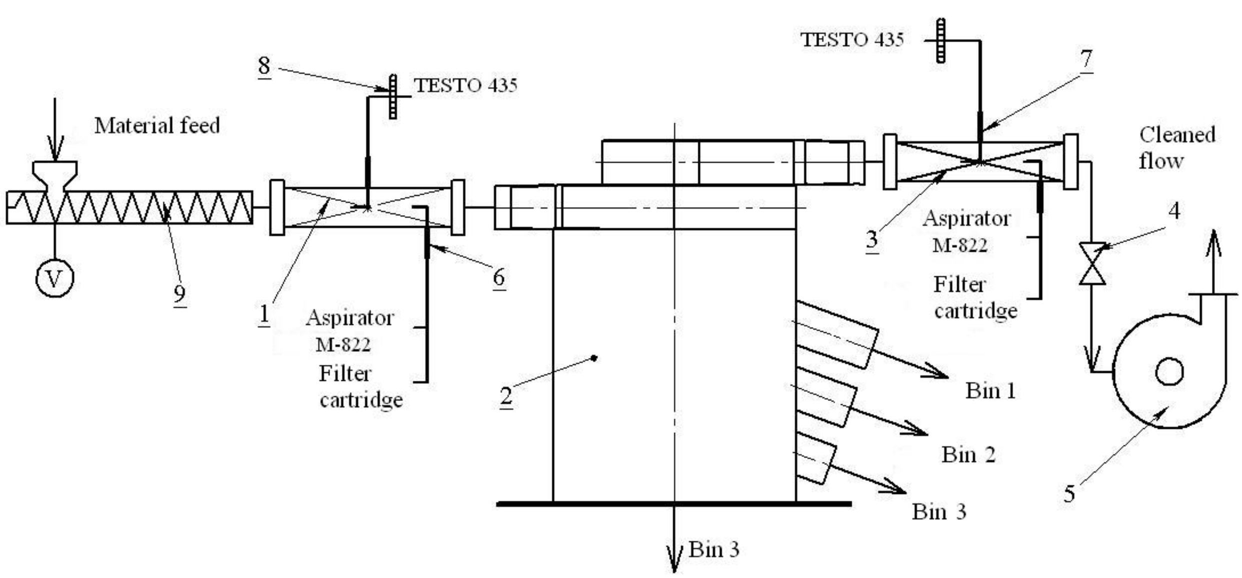

Fig. 1. The scheme of laboratory setup: 1, 3 — measuring flues; 2 — centrifugal filter; 4 — gate; 5 — centrifugal fan; 6, 7 — spouts for measuring experimental data; 8 — thermometer; 9 — screw feeder

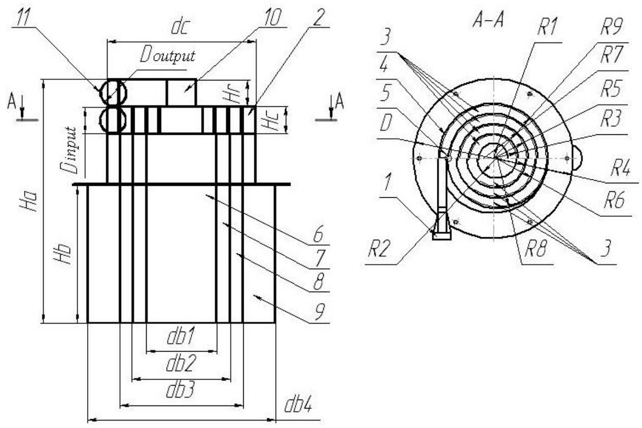

Fig. 2. Centrifugal filter: 1 — inlet; 2 — separation chamber; 3 — curvilinear channels; 4 — annular slots; 5 — recirculation gaps; 6–9 — bins; 10 — flow straightener; 11 — outlet

Operation of the centrifugal filter lies in the collection of particulates moving in the separation chamber 2 along the curved path and are concentrated at the periphery of each of the channels 3 and then removed through the gaps 5. Further, polydisperse particulates with the part of gas flow through the annular slots 4 to collectors 6–9, where a large amount of particulates settles, and those fractions that continue to soar, return to the active separation zone (channels) through the slot and are separated again. The most coarse particulates – from the first and second channels get to the bin 6, finer particulates from the third and fourth channels – to the bin 7, from the fifth and sixth channels – to the bin 8, the finest particulates from the seventh and eighth channels of the separation zone of the centrifugal classifier – to the bin 9. The gas flow cleaned from fine particulates is removed from the device through the outlet 11 through the flow straightener 10.

Particulate matter collected in the system of channels is removed through the annular slots of all four pairs of the eight-channel centrifugal dust collector to separate isolated bins.

4. 2. Techniques of pilot studies

For pilot studies, the air flow with the flow rate of 100...200 m^3/h and feed of particulates of 150...350 g/min was passed through the device. The studies were conducted at the mixture concentration of 100 g/m^3. Collection of particulates was carried out in 4 pairs of channels of different radius of curvature. Efficiency was determined for 3 operation modes of the device – 100, 150 and 200 m^3/h by weighing the amount of material, falling into the bin and the total amount of material fed during the experiment.

Dust of coke, kaolin, lime, cement, sand and lignin, whose properties are given in Table 1 were used as experimental materials in the studies. The materials used in pilot studies have a range of median diameter (d_{50}) of 12...50 mm and density ($\rho_п$) of 1800...3450 kg/m^3.

Based on pilot studies, particulate collection efficiency was determined for each pair of channels (bin number) for each type of dust. Materials of different median particulate diameter and density were used as dust.

The overall particulate collection efficiency (%) is determined in accordance with the expression (1):

$$\eta = \left[1 - \left(1 - \frac{\eta_1}{100}\right)\left(1 - \frac{\eta_2}{100}\right)\ldots\left(1 - \frac{\eta_n}{100}\right)\right]100, \quad (1)$$

where η is the overall particulate collection efficiency, %; η_1, η_2...η_n is the efficiency for each of the n bins of the device, %.

The results of experimental particulate collection efficiency determination for the four bins with different particulate diameters and the calculated values of the overall efficiency for kaolin are presented in Table 2.

Table 1

Properties of the materials used in pilot studies

Properties	coke	kaolin	lime	cement	lignin	sand
Density ($\rho_п$), kg/m^3	3450	3300	3260	3200	2300	1800
Median particulate diameter (d_{50}), mm	12	15	17	20	30	50
Dispersion, (σ)	2,8	2,5	3	3,1	2,2	2,9

Table 2

The results of experimental determination of kaolin particulate collection efficiency

Particulate diameter, mm	Particulate collection efficiency, % (for the four bins of the device)				Overall particulate collection efficiency, %
	1	2	3	4	
1	5,3	6,2	4,7	2,4	17,4
2,5	5,5	6,2	7,3	3,8	21
4	9	8,7	6	12,6	31,7
6,3	14,7	12,4	17,8	15,2	47,9
10	18	19	22,1	23	60,2
16	18,2	21,2	24,8	26	64,1
25	16	16	13,5	16	48,7
40	13,3	10,3	3,8	1	25,9

Similar studies were carried out for all materials presented in Table 1. Operation parameters of the device (temperature, flow rate, etc.) were maintained at the same level for all of the substances under study.

It can be expected from the data analysis results that the generalized relationship for all materials cannot be obtained at this stage, so further processing of the experimental data was carried out for each material separately.

5. The results of mathematical processing of experimental data for evaluating the overall particulate collection efficiency

The pilot studies found that there is a relationship between the overall collection efficiency of particulates and their diameter. Approximation was performed based on the approach [12], according to the specifics of the process. Verification of various types of single-factor relationships was held, the most promising is the functional relationship of the form (2):

$$y_i = \frac{x_i}{(a + bx + cx^2)}, \quad (2)$$

where y_i is the overall collection efficiency of the particulates of the i-type of material, %; x_i is the diameter of the particulates of the i-type of material, mm; a, b, c are unknown coefficients.

An example of determining the approximating relationship for kaolin particulates in the mathematical package Mathcad is shown in Fig. 3.

Summarized results of the mathematical relationships between the overall collection efficiency of particulates and their diameter for different materials are shown in Table 3.

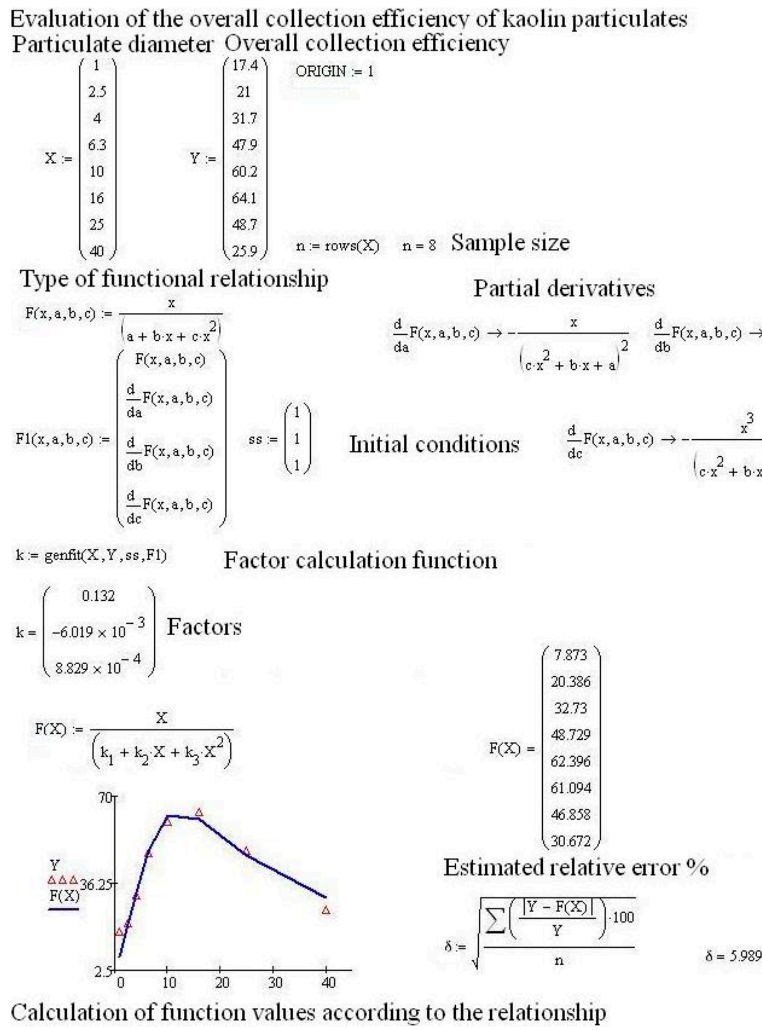

Fig. 3. Calculation of the type of the approximating relationship for evaluating the kaolin particulate collection efficiency in the Mathcad program

So, the mathematical relationships between the overall collection efficiency of particulates of different materials and their diameters are obtained, other properties (density, dispersion) remain fixed.

Evaluation of the correlation of parameters of particulates collected and relationship factors was performed (Fig. 4).

As seen from the results, there is a correlation between the density and the factor b. This means that the value of the overall material particulate collection efficiency is affected primarily by the particulate diameter, and the material density, as reflected in the values of the factor b. Therefore, research to establish a functional relationship between the collection efficiency of particulates and their diameter and the material density, as well as in collection of mixes of materials is promising. In addition, the studies found no significant effect of the material dispersion, which may be the result of maintaining fixed operation conditions of the centrifugal filter. This was also proved by calculations for evaluating the correlation between the parameters of material particulates and factors of approximating relationships. For final conclusions, investigation of the effect of dispersion of a wider range is advisable.

Table 3

The results of constructing the mathematical relationships of collection efficiency of particulates of different diameters

Type of solid material and its properties (density, kg/m^3, dispersion)	Form of the mathematical relationship for the efficiency evaluation, %	Estimated relative error, %
Coke, $\rho_п = 3450$, $\sigma = 2{,}8$	$\eta(d) = \dfrac{d}{(0.132 - 6.019 \cdot 10^{-3} d + 8.829 \cdot 10^{-4} d^2)}$	11,39
Kaolin, $\rho_п = 3300$, $\sigma = 2{,}5$	$\eta(d) = \dfrac{d}{(0.038 + 0.024 d - 1.627 \cdot 10^{-5} d^2)}$	5,99
Lime, $\rho_п = 3260$, $\sigma = 3$	$\eta(d) = \dfrac{d}{(0.024 + 0.022 d - 1.152 \cdot 10^{-4} d^2)}$	8,86
Cement, $\rho_п = 3200$, $\sigma = 3{,}1$	$\eta(d) = \dfrac{d}{(0.217 - 7.135 \cdot 10^{-3} d + 4.399 \cdot 10^{-4} d^2)}$	6,78
Lignin, $\rho_п = 2300$, $\sigma = 2{,}2$	$\eta(d) = \dfrac{d}{(0.416 - 0.018 d + 5.381 \cdot 10^{-4} d^2)}$	8,54
Sand, $\rho_п = 1800$, $\sigma = 2{,}9$	$\eta(d) = \dfrac{d}{(0.171 - 0.022 d - 2.182 \cdot 10^{-4} d^2)}$	8,53

Evaluation of the correlation of parameters of particulates collected and relationship factors

Density, Dispersion, Relationship factors a,b,c

$$\rho := \begin{pmatrix} 3450 \\ 3300 \\ 3260 \\ 3200 \\ 2300 \\ 1800 \end{pmatrix} \quad \sigma := \begin{pmatrix} 2.8 \\ 2.5 \\ 3 \\ 3.1 \\ 2.2 \\ 2.9 \end{pmatrix} \quad a := \begin{pmatrix} 0.132 \\ 0.038 \\ 0.024 \\ 0.217 \\ 0.416 \\ 0.171 \end{pmatrix} \quad b := \begin{pmatrix} -0.006019 \\ 0.024 \\ 0.022 \\ -0.007135 \\ -0.018 \\ -0.022 \end{pmatrix} \quad c := \begin{pmatrix} 0.0008829 \\ -0.001627 \\ -0.0001152 \\ 0.0004399 \\ 0.0005381 \\ -0.0002182 \end{pmatrix} \quad \begin{matrix} \text{Coke} \\ \text{Kaolin} \\ \text{Lime} \\ \text{Cement} \\ \text{Lignin} \\ \text{Sand} \end{matrix}$$

Correlation coefficients

$\mathrm{corr}(\rho, a) = -0.543$

$\mathrm{corr}(\rho, b) = 0.709$

$\mathrm{corr}(\rho, c) = -0.053$

Relationship

$\mathrm{corr}(\sigma, a) = -0.51$

$\mathrm{corr}(\sigma, b) = 0.099$

$\mathrm{corr}(\rho, c) = -0.053$

Fig. 4. Calculation of correlation of parameters of particulates collected and relationship factors in the Mathcad program

5. Discussion of results of the study of centrifugal filter efficiency

The advantages of the present research is construction of mathematical relationships, which allow calculating the particulate collection efficiency in the centrifugal filter of a new design for various types of dust. The downside is that finding the factors of the proposed relationship requires experimental tests of the types of dust that differ from the properties of the materials considered in the work.

Experimental data processing with obtaining appropriate mathematical relationships allows you to quickly determine the overall efficiency of cleaning of gas flows in the centrifugal filter for the design and operation forecasting of centrifugal filters.

First, the parameters affecting the efficiency of particulate collection by the centrifugal filter were analyzed in the paper. For this, aerodynamic tests were conducted, the analysis of which found that efficiency is significantly affected by a particulate size. Second, mathematical processing of research results was performed, namely the mathematical relationship was constructed to calculate the particulate collection efficiency for materials with the same parameters (diameter, density, dispersion) without conducting aerodynamic tests. To accomplish the task, it was decided to use built-in functions of the mathematical package Mathcad, which actually automated the process of calculating unknown factors of the proposed mathematical relationship and obtaining the efficiency value.

Further studies will be conducted to expand the database of factors of mathematical relationships for other materials.

6. Conclusions

As a result of the research:

1. Characteristics of the centrifugal filter for various materials: coke, kaolin, limestone, sand, lignin, cement were obtained. The collection efficiency of dust particulates of these materials during the pilot studies was 84...99 %.

2. The mathematical relationships of the particulate collection efficiency in the centrifugal filter of a new design were constructed. The relationship has the form of a hyperbolic function with three unknown factors. This choice is due to the results of aerodynamic research of the centrifugal filter. Using the mathematical package Mathcad, a search of unknown factors for various solid materials was carried out. The mathematical relationships of collection efficiency allow calculating the efficiency value with the known diameter of particulates for the material with the same parameters (density, dispersion, etc.).

Evaluation of the correlation of parameters of particulates collected and relationship factors was conducted. It was found that the overall collection efficiency of the particulates of the material is affected primarily by the particulate diameter, and the material density, as reflected in the values of the factors.

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ОБҐРУНТУВАННЯ ТА ФОРМАЛІЗАЦІЯ ПІДХОДУ ДО ОЦІНЮВАННЯ ЕКОЛОГІЧНОЇ БЕЗПЕКИ РЕГІОНУ

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Проведено аналіз причинно-наслідкових зв'язків у системі «людина-природа». Запропоновано та обґрунтовано підхід до впровадження положень концепції сталого розвитку зі зміщенням акценту на екологічну безпеку. Розраховано потенційну та реальну екологічну й економічну шкоду внаслідок нераціонального використання природних ресурсів. Запропоновано методи оцінювання індексу екологічної безпеки абіотичних та біотичних компонентів екологічних систем

Ключові слова: екологічна безпека, сталий розвиток, методи оцінювання, формалізація, екосистемний підхід, екологічна шкода

Проведен анализ причинно-следственных связей в системе «человек-природа». Предложен и обоснован подход к внедрению положений концепции устойчивого развития со смещением акцента на экологическую безопасность. Рассчитан потенциальный и реальный эколого-экономический ущерб вследствие нерационального использования природных ресурсов. Предложены методы оценивания индекса экологической безопасности абиотических и биотических компонентов экологических систем

Ключевые слова: экологическая безопасность, устойчивое развитие, методы оценивания, формализация, экосистемный подход, экологический ущерб

1. Вступ

В останні декілька років на рівні Організації Об'єднаних Націй (ООН) усе більшої актуальності набувають питання бідності та продовольчої безпеки. Це підтверджується при дослідженні тексту останніх глобальних документів у галузі забезпечення сталого розвитку – «Майбутнє, якого ми прагнемо» [1] та «Перетворення нашого світу: Порядок денний в сфері сталого розвитку на період до 2030 року» [2], де вирішення зазначених питань бачиться найважливішою глобальною задачею міжнародної спільноти та однією із необхідних умов забезпечення сталого розвитку.

Якщо замислитись над змістом проблем бідності та продовольчої безпеки, очевидним є їх тісний зв'язок: у регіонах, де досить складно виробити або добути харчування, часто спостерігається перенаселення і, як наслідок, виникають проблеми перерозподілу їжі. А там, де є бідність, завжди відсутні можливості повного задоволення потреб людей у харчах. Виходить своєрідне замкнене коло.

З точки зору категорій, вище визначені проблеми можна сміливо віднести до соціальних, однак їх дослідження тільки під таким кутом зору буде великою помилкою. Адже соціальна сутність людини є лише одним із проявів буття людини, яку можна охарактеризувати і з економічної, і з екологічної точки зору.