Measurement of Impurity Concentration in Turbulent Flows of Ventilation Systems Channels

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Abstract. The work is devoted to the experimental study of the process of impurities diffusion in the circular cylindrical channel and the determination of the coordinates of the average concentration of impurities in the turbulent flow. To ensure the uniformity for the aerosols composition during the studies, the experiments were carried out with solid particles of narrow fractional composition. The use of fine-grained oxide catalyst made it possible to obtain the almost monodisperse material. The experimental installation included the volumetric doser for impurity material, the ejector, the concentration sensor, the section of the vertical pipeline, and manometers for recording the pressure in the system. It is shown that the theoretical and experimental results are in satisfactory agreement with each other, and the existing discrepancy can be explained both by the measurement error and by the presence of spiral motion for the solid phase in the ascending flow. Based on the experiments, it was concluded that the known mathematical positions are adequate and internally not contradictory models of the diffusion process of the impurity substance in the channels of the ventilation systems. The results of the studies performed should be taken into account when developing systems for measuring and monitoring the gas-air emissions characteristics of the ventilation systems of industrial enterprises.

1. Introduction

Industrial emissions are the main source of environmental pollution. These emissions are carried out by such engineering structures as the ventilation systems and are due to the conduct of industrial technological processes [1-5]. In addition, gas-air emissions ensure the maintenance of the required sanitary and hygienic standards in industrial buildings and premises. Waste emissions from industrial activities are harmful to human health and the environment. The most acute problem of technogenic safety is determined by emissions from industrial enterprises in the energy, mining, metallurgical, chemical and oil refining industries [6-10].

The reliable forecast of the volume and composition of emissions allows you to effectively solve the problems of preventive and repair work, planned and long-term measures for the modernization of the ventilation systems, correction of production technological processes, simulate possible emergency
situations, develop recommendations for improving environmental safety, etc. [11-15] The measurement of impurity concentration in the turbulent flows of the ventilation systems channels is the integral and important task in monitoring the characteristics of emissions from industrial enterprises.

2. Analysis of recent achievements and publications

The distribution of impurity concentration in the flow over the cross section of the ventilation channel is not uniform, therefore, the accuracy and reliability of control largely depends on the installation place of intake devices and sensors for measuring concentration [16-20]. To analyze the regularities of diffusion processes in the ventilation systems channels, extensive mathematical apparatus has been developed, which makes it possible to study the concentration distribution in the flow using examples of the typical impurity sources [21-25]. However, a number of known theoretical positions require experimental confirmation, especially, this refers to the recommendations presented in the literature on the concentration distribution over the channel cross-section and, first of all, concerns the determination of the cross-section coordinates that correspond to the average impurity concentration in the flow.

It should be noted the well-known solution [26] of the problem for diffusion of the circular source of the radius \( R_s \) in the flow in the circular cylindrical channel of the radius \( R_0 \)

\[
\bar{C}(x, \tau, \bar{r}) = \frac{C_0}{\sqrt{x}} \sum_{n=0}^{\infty} \exp \left( -\mu_n^2 \frac{4(\tau - \tau)}{Pe_d} \right) \frac{J_n(\mu_n \bar{r})}{\mu_n J_0(\mu_n)} f_1 \tag{1}
\]

where \( \bar{C} = C / C_0 \) – dimensionless concentration \( C \) (\( C_0 \) – average concentration); \( \bar{x} = x / d \); \( \bar{r} = r / R_0 = 2r / d \) – dimensionless axial coordinate \( x \) and dimensionless radius \( r \) (\( d = 2R_0 \) – channel diameter); \( \bar{\tau} = \tau = R_s / R_0 = 2R_s / d \) – dimensionless source radius; \( \tau = t u_0 / d \) – dimensionless time \( t \); \( Pe_d = ReSc \) – diffusion Peclet number (\( Re \) – Reynolds number; \( \nu \) – kinematic viscosity; \( Sc \) – Schmidt number [27-30]); \( J_0 \) and \( J_1 \) – Bessel functions of the first kind of the zero and first order [22]; \( \mu_n \) – roots of the equation

\[
J'_0(\mu) = 0 \tag{2}
\]

3. Purpose of the research

The purpose of this paper is to experimentally study the process of impurity diffusion in the circular cylindrical channel and to determine the coordinates of the average concentration of impurity in the turbulent flow.

4. Materials and results of the research

The study of the diffusion process was carried out on the operating industrial installation of the vertical pneumatic transport (Fig. 1) with the pipeline diameter of 200 mm and length of 15 meters. It is practically impossible to ensure the uniformity of the aerosol composition during the experiments; therefore, the experiments were carried out with solid particles of narrow fractional composition (practically with monodisperse material, which was used as fine-grained oxide catalyst), which made it possible to reveal the structure of the two-phase flow. The installation contained the volumetric doser of the transported material 1, the ejector 2, the concentration sensor 3, the section of the vertical pipeline 4, and manometers MN1 ...
MN4 for recording the pressure in the pneumatic transport system. The average weight flow rate of the catalyst and transporting air was measured by standard flow meters, not shown in the scheme.

The installation scheme.

The installation was used to study the distribution of local concentrations of solid fine-grained monodisperse material in the ascending air flow. Analysis of methods and devices for determining local impurities concentrations in the gas flows showed that the most acceptable in terms of accuracy and simplicity are indirect methods based on the use of various physical effects, in particular, the capacitive method. It is based on a change in the capacitance of a capacitor when an impurity is localized between its linings. Theoretical analysis of static and dynamic characteristics, preliminary calibration (using the standard weight method) showed that the error in determining the local impurity concentration did not exceed 7%.

Preliminary experiments have shown that even in the same place at the stationary gas flow in the pipeline, there are pulsations of the impurity concentration. In addition, visual observations through the transparent walls of the pneumatic elevator showed that some spiral motion of the solid phase occurs in the ascending flow. Therefore, the average value of the concentration $C$ was calculated over the time at each measurement point

$$C = \frac{\sum_{i=1}^{n} C_i}{n},$$

(3)

where $n$ – number of experiments at the given point, which was at least 10.

In order to reduce the number of experiments while maintaining the reliability of the obtained data, the method of orthogonal planning was applied.

The gas velocity $V$ in the pipeline under normal operating conditions was approximately 20 m/s, the step of variation was chosen equal to 5 m/s. The numerical values of the physical parameters used in the experiment are given in Table. I.
Table 1. The Values of Variable Parameters.

| Level | Parameters | Reynolds number Re | Vertical coordinate $R_1$, mm | Horizontal coordinate $R_2$, mm | Normalized values |
|-------|------------|--------------------|-------------------------------|-------------------------------|------------------|
| Main level | gas velocity $V$, m/s | 20 | 2.5 | $10^5$ | 0 | 0 | 0 |
| Upper level | | 25 | 3.125 | $10^5$ | 60 | 60 | 1 |
| Lower level | | 15 | 1.875 | $10^5$ | -60 | -60 | -1 |
| Variation interval | | 5 | 6.25 | $10^4$ | 60 | 60 | 0 |

The planning matrix is shown in Table II.

In the table, $\bar{C} = C/C_0$ denotes the relative value of the impurity concentration, defined as the ratio of the current time-averaged concentration $C$ measured by the sensor, to its average value $C_0$, calculated from the readings of the impurity and gas flow meters. The location of the measurement points for the concentration of the impurity substances in the pipeline section is shown in Fig. 2.

The response function was determined by approximating the values of $\bar{C}$ in the form of a second-order polynomial

$$\bar{C}_p = b_0 + b_1 R_1 + b_2 R_2 + b_3 R_1 R_2 + b_4 R_1^2 + b_5 R_2^2 + b_6 R_1 R_2^2 + b_7 R_1^2 R_2 + b_8 R_2^3 + b_9 R_1 R_2 R_3 + b_{10} R_1^2 R_2 R_3 + b_{11} R_2^2 R_3 + b_{12} R_1 R_2 R_3^2 + b_{13} R_1^2 R_2 R_3^2 + b_{14} R_2^2 R_3 R_4 + b_{15} R_1 R_2 R_3 R_4 + b_{16} R_1^2 R_2 R_3 R_4$$

(4)

where $b_0, \ldots, b_{16}$ = coefficients of the response function equation.

Table 2. The Values of Variable Parameters

| N | Normalized Parameters | $R_1$ | $R_2$ | $\bar{C}$ | $\bar{C}_p$ |
|---|------------------------|-------|-------|----------|-----------|
| 1 | +1                     | +1    | +1    | 0.79     | 0.81\_3   |
| 2 | -1                     | +1    | +1    | 0.80     | 0.81\_3   |
| 3 | +1                     | -1    | +1    | 0.90     | 0.88\_3   |
The experimental values of the concentration of the impurity substance have the systematic and random error. The predominant one is the random, the systematic is minimized by preliminary calibration of the concentration sensor, therefore, to calculate the response function coefficients, the least squares method was used, which corresponds to the maximum likelihood of the obtained equation. After processing the experimental data, the equation for the response function was obtained in the form

\begin{center}

| N | Normalized Parameters | \( \mathcal{C} \) | \( \mathcal{C}_p \) |
|---|-----------------------|----------------|----------------|
| 4 | -1 -1 +1              | 0.91 0.88      |                |
| 5 | +1 +1 -1              | 0.78 0.81      |                |
| 6 | -1 +1 -1              | 0.80 0.81      |                |
| 7 | +1 -1 -1              | 0.83 0.88      |                |
| 8 | -1 -1 -1              | 0.85 0.88      |                |
| 9 | 0 0 0                 | 1.20 1.21      |                |
| 10| +1.21 0 0             | 1.20 1.21      |                |
| 11| -1.215 0 0            | 1.21 1.21      |                |
| 12| 0 +1.215 0            | 0.97 0.94      |                |
| 13| 0 -1.215 0            | 1.02 0.94      |                |
| 14| 0 +1.215 0            | 0.90 0.90      |                |
| 15| 0 -1.215 0            | 0.92 0.90      |                |

\end{center}

\textbf{Figure 2.} The coordinates of the concentration measurements points.

The experimental values of the concentration of the impurity substance have the systematic and random error. The predominant one is the random, the systematic is minimized by preliminary calibration of the concentration sensor, therefore, to calculate the response function coefficients, the least squares method was used, which corresponds to the maximum likelihood of the obtained equation. After processing the experimental data, the equation for the response function was obtained in the form
\[ C_p = 1.2194 - 0.0065 \Re - 0.0348 \Re l + \]
\[ + 0.0106 \Re r - 0.0141 \Re l^2 - 0.1565 \Re l^3 - 0.2139 \Re l^4 - 9.3689 \times 10^{-6} \Re e \Re l - 0.0025 \Re e \Re r - 0.0150 \Re l \Re r. \]  

(5)

Due to the normalization of the factors and the orthogonality of the planning matrix, variances and confidence intervals for all coefficients of the response function are equal.

The equation coefficient is significant if its absolute value is greater than the confidence interval. The narrower the confidence interval, the more confidently we can speak about the significance of the coefficient. Such check of the coefficients significance of the response function equation made it possible to somewhat simplify it

\[ C_p = 1.219 - 0.035 \Re l - 0.157 \Re l^2 - 0.214 \Re l^2. \]  

(6)

To check the adequacy of the approximation model, the Fisher criterion was used.

A preliminary analysis of the results obtained showed that the distribution of the concentration of the impurity substance is practically independent of the Reynolds number. This result can be explained by the fact that, on the one hand, increase in the velocity of the transporting gas (increase in the Reynolds number) leads to increase in the turbulence degree, on the other hand, the transit time of the particle from the impurity source to the measuring point is reduced.

The response function is practically symmetrical about the pipeline center and has the maximum at its center. This result is explained by the fact that the calculation includes the time-averaged values of the concentration at each measurement point (previously, the presence of rotational gas movement in the pipeline was noted). The presence of the maximum concentration in the pipeline center does not contradict the experimental data available in the literature, where it is noted that during pneumatic conveying of fine-grained material, solid particles perceive turbulent gas pulsations to greater extent; therefore, the concentration profile is close to the gas velocity profile.

Especially noteworthy is the estimate of the radius of the average impurities concentration in the flow. According to the above theoretical positions, for the experimental channel with the diameter of 200 mm, this radius should be 62 mm. On the basis of the experiment, the points in the channel cross-section corresponding to the average concentration can be established from the response function by substituting \( C_p = 1. 

The theoretical circle 1 and curve 2, established according to experimental data, corresponding to the average value of the impurity concentration, are compared in Fig. 3. As can be seen, the results are in satisfactory agreement with each other, and the existing discrepancy can be explained both by the measurement error and by the presence of a spiral motion of the solid phase in the ascending flow.

V. CONCLUSIONS

Thus, experimental studies of the process of impurity diffusion in the circular cylindrical channel have been carried out and the coordinates of the average concentration of impurity in the turbulent flow have been estimated.

To ensure the uniformity for the aerosols composition during the studies, the experiments were carried out with solid particles of narrow fractional composition. The use of fine-grained oxide catalyst made it possible to obtain the almost monodisperse material. The experimental installation included the volumetric doser for impurity material, the ejector, the concentration sensor, the section of the vertical pipeline, and manometers for recording the pressure in the system.

It is shown that the theoretical and experimental results are in satisfactory agreement with each other, and the existing discrepancy can be explained both by the measurement error and by the presence of spiral
motion for the solid phase in the ascending flow. Based on the experiments, it was concluded that the well-known mathematical positions are adequate and internally not contradictory models of the diffusion process of the impurity substance in the turbulent flow, which can be used to analyze the distribution of the impurity concentration in the channels of the ventilation systems.

The results of the studies performed should be taken into account when developing systems for measuring and monitoring the gas-air emissions characteristics of the ventilation systems of industrial enterprises.

![Diagram](image)

**Figure 3.** The lines of the average concentration: theoretical (1) and experimental (2).

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