Simulation Studies of Numerical Relationship of Sewage Energy Dissipation Chamber Efficiency

I Stolbikhin and A Semenov

Saint Petersburg State University of Architecture and Civil Engineering, 2nd Krasnoarmeyskaya st., 4, 190005, Saint-Petersburg, Russia

E-mail: sw.semenov@gmail.com

Abstract. The paper introduces a computer model to simulate design of an energy dissipation chamber (EDC). This model allows expressing the air flow rate through the system as a function of the incoming effluent rate. A method is developed to proceed with statistical analysis of simulation results. A set of plots of air flow rate is developed for effluent rates under different parameters of energy dissipation chamber. The approximating function and coefficients allowing obtaining the air consumption under certain conditions (geometrical parameters of the energy dissipation chamber and the effluent rate) are represented. The graphs are obtained in the form of three-dimensional surfaces reflecting a dependence of the ejected air flow rate on the incoming sewage liquid rate for at various values of the stand pipe embedment relative to the liquid level. The developed graphs show that the highest air flow rate is achieved at the maximum water flow rate and at the minimum embedment. Thus, the numerical dependences of the ejected air flow rates were obtained for the energy dissipation chamber as functions of the water flow rate. The embedment of the stand pipe at the level of the overflow wall and the zero inlet radius are shown to be the most effective parameters of energy dissipation chamber design.

1. Introduction

The design of sewage systems often provides for areas featuring merging pump and gravitational flow streams. These areas are known as energy dissipation chamber (EDC) and usually they are designed underground. Professor V. M. Vasiliev (DSc in Engineering) and I. V. Stolbikhin (PhD in Engineering) [1, 2] developed a new design of EDC having a significant advantage over known designs. The advantage deals with air ejecting pipe delivering air to the falling sewage liquid flow. This design solution allows saturating the effluent with air oxygen which mitigates microbiological corrosion — the most aggressive factor in sewage systems [3–5]. The main elements of the energy dissipation chamber structural design are shown in figure 1.

This design allows preventing corrosion and dissipating the energy of the falling liquid. In previous papers [2] it was found that embedment of the stand pipe to a certain level (rather than free water flow rate on the liquid surface in the stilling reservoir) ensured air influx into the bend-stand pipe system due to developing jet separation (see figure 1). This area reduces pressure and the atmospheric air enters the system from the daylight surface. The higher the air flow rate, the better mitigation of microbiological corrosion process is [2, 6]. Therefore, studying this issue is interesting from the practical standpoint.

In this paper, we simulated the throughput of ejected air in the energy dissipation chamber against water flow rate which enabled us finding the most effective EDC design parameters.
2. Materials and methods
In order to solve this problem, the computer model of the energy dissipation chamber was developed using ANSYS CFX software package [7]. The general structure of the computer model showing boundary conditions (b. c.) is shown in figure 2.
Figure 2. Computer model of the energy dissipation chamber developed using ANSYS CFX.

ANSYS CFX package is based on the mathematical model using Reynolds-averaged system of Navier–Stokes equations to simulate behavior of liquid. This approach is used to examine a series of similar applied problems [8].

It should be noted that the system of Navier–Stokes equations also involves standard $k - \varepsilon$ turbulence model.

In simulations, the size of mesh was set at $8.7 \cdot 10^{-4}$ m. We selected the multiphase model of homogeneous type to improve convergence. Parameter ‘specified blend factor’ was set at 0.75. The time scale was set as automatic specifying the length of the fluid particle path inside the pool as equal to 3 m. The problem was solved through 500 iterations which is recommended as sufficient by the software developers [7].

3. Numerical results

In accordance with the above described computer model, we simulated a series of certain realizations of the problems. The following parameters were taken: the embedment value for the level of liquid $\Delta$, the incoming liquid flow rate $Q_w$. Depending on the flow rate, the diameter of the stand pipe $d_0$ was estimated.

Shown below is an example of the first group of experiments in which the mathematical processing of the simulation data was conducted. This process can be described as a series of the following steps:

1) Populating the table with the data obtained as a result of computer simulation (table 1).
2) The following graph was developed using the data obtained (figure 3).
3) Microsoft Excel package was used to plot the trend lines and obtain the approximation equations using quadratic polynomial functions (table 2).
4) This was followed by compiling a table of coefficients of approximating function $A, B$ and $C$ for each value of embedment $\Delta$, mm (table 3). The coefficients had accuracy of 10 decimal points which allows obtaining a reliable overall function. Decreasing the accuracy of coefficients to 2 decimal points results in the inaccuracy exceeding 10%. 


Table 1. Values of the ejected air flow rate $Q_{ej} \cdot 10^3$ l/s at various values of water flow rate $Q_w$ and embedment $\Delta$.

| $Q_w$, l/s | 0   | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 30         | 13.12236 | 10.12658 | 8.531646 | 6.421941 | 6.244726 | 5.443882 | 4.896203 | 4.150211 |
| 45         | 14.36287 | 11.55274 | 10.91139 | 9.400844 | 8.455696 | 7.548523 | 7.262447 | 6.437975 | 6.206751 |
| 60         | 14.39662 | 12.86076 | 11.72996 | 10.40506 | 9.755274 | 9.021097 | 8.265823 | 7.967089 | 7.327426 |
| 75         | 15.38397 | 13.64557 | 13.39241 | 11.93249 | 11.18143 | 11.1308 | 10.44726 | 10.07595 | 9.780591 |
| 90         | 16.16034 | 15.35865 | 14.98734 | 14.01020 | 13.32489 | 12.98734 | 12.55696 | 12.12658 | 10.58228 |
| 105        | 17.02954 | 16.43882 | 16.62447 | 16.02031 | 15.78059 | 14.93671 | 13.83966 | 11.34177 | 14.65823 |

Figure 3. Results of simulation; the ejected air consumption rate $Q_{ej}$ plotted as a function of water flow rate $Q_w$ for the first group of experiments.
Table 2. Quadratic polynomial approximation equations obtained for the first group of experiments.

| Δ , mm | Approximation equation \( Q_{ej} = A \cdot Q_w^2 + B \cdot Q_w + C \) |
|--------|-------------------------------------------------|
| 0      | \( Q_{ej} = 0.0884066707 \cdot Q_w^2 + 37.4281695801 \cdot Q_w + 12 \, 088.7281494877 \) |
| 100    | \( Q_{ej} = -0.0087067176 \cdot Q_w^2 + 84.5348635576 \cdot Q_w + 7669.8010849909 \) |
| 200    | \( Q_{ej} = -0.0482218204 \cdot Q_w^2 + 110.0421940928 \cdot Q_w + 5519.7106690777 \) |
| 300    | \( Q_{ej} = -0.0509008104 \cdot Q_w^2 + 127.2814948764 \cdot Q_w + 3033.8758288125 \) |
| 400    | \( Q_{ej} = 0.6335811399 \cdot Q_w^2 + 29.3791440627 \cdot Q_w + 5617.6009644364 \) |
| 500    | \( Q_{ej} = 0.3780724667 \cdot Q_w^2 + 66.8384569017 \cdot Q_w + 3829.2344786016 \) |
| 600    | \( Q_{ej} = 0.1385707588 \cdot Q_w^2 + 95.6622463331 \cdot Q_w + 2456.5039180228 \) |
| 700    | \( Q_{ej} = -0.7576853526 \cdot Q_w^2 + 200.1971066908 \cdot Q_w - 756.2748643761 \) |
| 800    | \( Q_{ej} = 0.7000870672 \cdot Q_w^2 + 35.2403054049 \cdot Q_w + 2756.3230861964 \) |

Table 3. Coefficients \( A, B, C \) of the approximating polynomial obtained for each value of \( \Delta \).

| Δ , mm | \( A \) | \( B \) | \( C \) |
|--------|--------|--------|--------|
| 0      | 0.0884066707 | 37.4281695801 | 12 088.7281494877 |
| 100    | 0.0087067176  | 84.5348635576  | 7669.8010849909   |
| 200    | -0.0482218204 | 110.0421940928 | 5519.7106690777   |
| 300    | -0.0509008104 | 127.2814948764 | 3033.8758288125   |
| 400    | 0.6335811399  | 29.3791440627  | 5617.6009644364   |
| 500    | 0.3780724667  | 66.8384569017  | 3829.2344786016   |
| 600    | 0.1385707588  | 95.6622463331  | 2456.5039180228   |
| 700    | -0.7576853526 | 200.1971066908 | -756.2748643761   |
| 800    | 0.7000870672  | 35.2403054049  | 2756.3230861964   |

Based on the above data, the corresponding graphic dependences were plotted (figure 4). The trend lines were obtained for these dependences as well and they were quadratic polynomials. Thus, here we assign index ‘\( A \)’ to the first curve (\( A \)), the second (\( B \)) curve has index ‘\( B \)’, and the third (\( C \)) curve has index ‘\( C \)’.

As is seen from figure 4, increasing the embedment value \( \Delta \) results in growing the value of coefficient ‘\( A \)’ in front of the quadratic term indicating the growing dominance of nonlinear behavior.
Figure 4. Values of coefficients $A, B, C$ plotted as functions of the embedment parameter $\Delta$.

In general terms, the equation describing $Q_{aj}$ as a function of $Q_w$ and $\Delta$ can be written as follows:

$$Q_{aj} = (A_A \cdot \Delta^2 + B_A \cdot \Delta + C_A)Q_w^2 + (A_B \cdot \Delta^2 + B_B \cdot \Delta + C_B)Q_w + (A_C \cdot \Delta^2 + B_C \cdot \Delta + C_C)$$

(1)

here coefficients $A_A - C_C$ depend on parameters of the pool and they are obtained through approximation described above.

When the coefficients obtained as well as values $Q_w$ and $\Delta$ are substituted into equation (1) we obtain a set of data (table 4).

4. Results and discussion

According to the data shown in Table 4, a three-dimensional surface can be developed (see figure 5).
Table 4. Values of the ejected air flow rate $Q_{ej} \cdot 10^3$ l/s at various values of water flow rate $Q_w$ and embedment $\Delta$ (processed data).

| $Q_w$, l/s | $\Delta$, mm |
|-----------|-------------|
| 0         | 30          | 45          | 60          | 75          | 90          | 105         |
| 100       | 12.64393    | 13.51129    | 14.39205    | 15.2862     | 16.19375    | 17.11468    |
| 200       | 9.047492    | 10.403      | 11.80004    | 13.23862    | 14.71874    | 16.69007    |
| 300       | 7.651999    | 9.170064    | 10.74046    | 12.36319    | 14.03825    | 16.24039    |
| 400       | 6.524991    | 8.151276    | 9.838503    | 11.58667    | 13.9578     | 15.76565    |
| 500       | 5.666468    | 7.346633    | 9.094163    | 10.90906    | 12.79132    | 15.26583    |
| 600       | 5.07643     | 6.756134    | 8.507443    | 10.33036    | 12.22487    | 14.74095    |
| 700       | 4.754875    | 6.379779    | 8.078341    | 9.850562    | 11.69644    | 13.61598    |
| 800       | 4.701806    | 6.217569    | 7.806859    | 9.469676    | 11.20602    | 13.01589    |

Figure 5. Values of the ejected air flow rate $Q_{ej}$ at various values of water flow rate $Q_w$ and embedment $\Delta$ obtained for group of experiments No. 1.

Figure 5 shows that the embedment significantly affects the flow rate of ejected air. The minimum embedment corresponds to the maximum point at the maximum water intake.

Figures 6–11 depict the surfaces obtained as a result of the same mathematical processing of the rest of the simulation data. These surfaces correspond to the groups of experiments having parameters shown in table 5. These results indicate that in all cases the minimum flow rate of ejected air corresponds to the maximum embedment.
Figure 6. Values of the ejected air flow rate $Q_{ej}$ at various values of water flow rate $Q_w$ and embedment $\Delta$ for groups of experiments No. 2.

Figure 7. Values of the ejected air flow rate $Q_{ej}$ at various values of water flow rate $Q_w$ and embedment $\Delta$ for groups of experiments No. 3.
Figure 8. Values of the ejected air flow rate $Q_{ej}$ at various values of water flow rate $Q_w$ and embedment $\Delta$ for groups of experiments No. 4.

Figure 9. Values of the ejected air flow rate $Q_{ej}$ at various values of water flow rate $Q_w$ and embedment $\Delta$ for groups of experiments No. 5.
Figure 10. Values of the ejected air flow rate $Q_{ej}$ at various values of water flow rate $Q_w$ and embedment $\Delta$ for groups of experiments No. 6.

Figure 11. Values of the ejected air flow rate $Q_{ej}$ at various values of water flow rate $Q_w$ and embedment $\Delta$ for groups of experiments No. 7.

Note. Three options of inlet radius $R_m$ were considered: $R_m = 0d_0$ (connection of a horizontal pipeline to the stand pipe at the right angle), as well as $R_m = 0.5d_0$ and $R_m = 0.75d_0$ to model steel stand pipes manufactured by vendors.

The data presented show that the embedment of the stand pipe at the level of the overflow wall ($\Delta = 0$) has better efficiency if compared to the maximum embedment ($\Delta = 800$ mm) by a factor of 10.
Based on the obtained results, we can conclude that the most effective parameters of the energy dissipation chamber are associated with embedment of the stand pipe at the level of the overflow wall as well as with the zero inlet radius ($R_{in} = 0d_0$).

**Table 5.** Groups of experiments to estimate the ejected air flow rate as a function of $\Delta$ and $Q_w$ at different geometrical parameter of the pool.

| Experimental series number | Diameter of the stand pipe, $d_0$, mm | Diameter of the ejecting pipe, $d_{ej}$, mm | Range of water flow rate, $Q_w$, l/s | Range of embeddings of the stand pipe, $\Delta$, mm | Radius of inlet $R_{in}$, mm | $L - \Delta$, mm |
|----------------------------|---------------------------------------|----------------------------------------------|----------------------------------------|------------------------------------------|--------------------------|----------------|
| 1                          | 200                                   | 75                                           | 30 − 105                               | 0 − 800                                  | 0.75$d_0$               | 500            |
| 2                          | 300                                   | 75                                           | 75 − 200                               | 0 − 800                                  | 0.75$d_0$               | 500            |
| 3                          | 400                                   | 75                                           | 125 − 275                              | 0 − 800                                  | 0$d_0$                  | 500            |
| 4                          | 500                                   | 75                                           | 200 − 575                              | 0 − 800                                  | 0.5$d_0$                | 1000           |
| 5                          | 500                                   | 75                                           | 200 − 575                              | 0 − 800                                  | 0$d_0$                  | 1000           |
| 6                          | 600                                   | 75                                           | 300 − 800                              | 0 − 800                                  | 0$d_0$                  | 1000           |
| 7                          | 800                                   | 200                                          | 500 − 1500                             | 0 − 800                                  | 0$d_0$                  | 1000           |

5. Conclusions

As a result of mathematical processing of computer simulation data, the authors obtained graphs in the form of three-dimensional surfaces reflecting a dependence of the ejected air flow rate on the incoming sewage liquid rate for at various values of the stand pipe embedment relative to the liquid level. The graphs developed show that the highest air flow rate is achieved at the maximum water flow rate and at the minimum embedment. The data obtained formed the basis to generate the methods to calculate the energy dissipation chamber design geometry parameters.

Thus, the numerical dependences of the ejected air flow rates were obtained for the energy dissipation chamber as functions of the water flow rate. The embedment of the stand pipe at the level of the overflow wall as well as the zero inlet radius are shown to be the most effective parameters of energy dissipation chamber design.

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