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# FLOW VISUALIZATION OF FLUE GASES IN MULTI-TUBE ELECTROSTATIC PRECIPITATORS USING CFD SIMULATIONS

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**Abstract:** Particulate matter capture is a necessary concern for safeguarding human health and quality of life. This article focuses on enhancing particulate matter capture efficiency via electrostatic precipitation. It deals with expanding the fundamental principle of the single electrode in chimney tubular precipitator to a configuration with multi-tubular precipitation chambers with the aim of increasing the collection area and consequently enhancing the overall efficiency of the separator. The velocity distribution of flue gases was observed through Computational fluid dynamics using Ansys Fluent. The collection area for each proposed separator was calculated, including its enlargement, and the flow uniformity of flue gases through the tubes was assessed. Increasing the number of tubes from one to three resulted in 1.3 times an increase in the collection area. Further expansions to 4, 5, and 7 tubes led to increases of 1.6, 1.7, and 2.1 times, respectively. It was found that due to non-uniform flow distribution through the tubes, the flue gas velocities varied, with values ranging from 0.186 to 1.178 m. $s^{-1}$. Non-uniform gas flow prevents full utilization of the separator potential, thereby reducing its efficiency. For uniform flow, it would be appropriate to seek a suitable solution for a flow straightener. Additionally, the high particle velocities should be avoided to prevent particles from being carried out of the stack with the flue gas, allowing sufficient time for capture.
**Keywords:** computational fluid dynamics, electrostatic precipitator, particulate matter, emission reduction, tubular separator

## 1. INTRODUCTION

Particulate matter (PM) constitutes a significant emission component of air pollution (Elbl et al., 2022). Elevated concentrations of PM adversely impact human health, causing respiratory and other diseases that substantially reduce both the quality and duration of life (Drga et al., 2022; Singh et al., 2021). Electrostatic precipitators have found widespread application in industrial settings and play a crucial role in environmental

protection. An electrostatic precipitator (ESP) can operate with a high collection efficiency while maintaining a low pressure drop (Mizuno, 2000). Therefore, EPS represents a promising avenue for environmental sustainability. In conjunction with low-emission fuels, they can effectively rival alternative heating technologies that are gaining popularity in contemporary society (Holubčík et al., 2024, 2022).
The issue of particulate matter emissions from domestic heating appliances, such as boilers, furnaces, masonry heaters, fireplaces, and stoves, remains unresolved (Jaworek et al., 2024). Over the past two decades, various designs of domestic boilers with a rated heat output below 50 kW have been developed for individual homes. These boilers aim to reduce PM emissions when burning various types of biomass, including logs, pellets, or coal (Lasek et al., 2018). Different labyrinthine or obstructive structures within the flue gas ducts are employed to capture particulate matter through inertial separation. However, this method is ineffective for submicron and nanoparticles. Therefore, electrostatic precipitators for micro and submicron particles and heat exchangers for thermophoretic removal of ultrafine particles have been recommended (Grigonytė-Lopez Rodriguez et al., 2020; Jaworek et al., 2021; Lim et al., 2015).
Jaworek further stated that it has been demonstrated that three challenges must be addressed in the case of small electrostatic precipitators: (1) increasing collection efficiency to a level exceeding 99%, (2) implementing automatic electrode cleaning without disrupting the gas cleaning process, and (3) ensuring stable operation in domestic environments, regardless of the fuel utilized by the user (Jaworek et al., 2024).
Recent trends have moved towards the utilization of computational fluid dynamics (CFD) in favor of theoretical correlations to model electrostatic precipitator (ESP) processes. This shift aims to optimize fluid flow and ESP dimensions, thereby enhancing ash collection efficiency. The intricate flow dynamics within ESPs can be effectively simulated using CFD, and by integrating electrostatic and particle dynamics into the numerical models, it is possible to predict particle trajectories and collection efficiencies (Arif et al., 2016; Farnoosh et al., 2010; Long and Yao, 2010). Researchers like Ahmadi et al., Guo et al., Li et al., Skodras et al., Arif et al. have used CFD models to study electric field distribution, PM trajectories, numbers of trapped particles, and more. This article investigates the expansion of a tubular electrostatic precipitator into a multi-tubular precipitator with the aim of increasing the collection area and consequently enhancing the overall efficiency of the separator. The velocity distribution of flue gases was observed through CFD simulations using Ansys Fluent. The collection area for each proposed separator was calculated, including its enlargement, and the flow uniformity of flue gases through the tubes was assessed.

## 2. METHODOLOGY OF RESEARCH

The model was developed based on the CFD simulations in Ansys Fluent. The tubular electrostatic precipitator was expanded into a multi-tubular precipitator as follows: 3-tubular, 4-tubular, 5-tubular and 7-tubular. Individual models are stated in Fig. 1. The expansion involved a progressive transition from a single 300 mm diameter tube, 350 mm in length, to a system comprising 3 tubes with a 130 mm diameter, 4 tubes with a 120 mm diameter, 5 tubes with a 100 mm diameter, and 7 tubes with a 90 mm diameter. The diameter of each tube was determined based on the available space within the main pipe and the standardized dimensions of the smaller pipes.

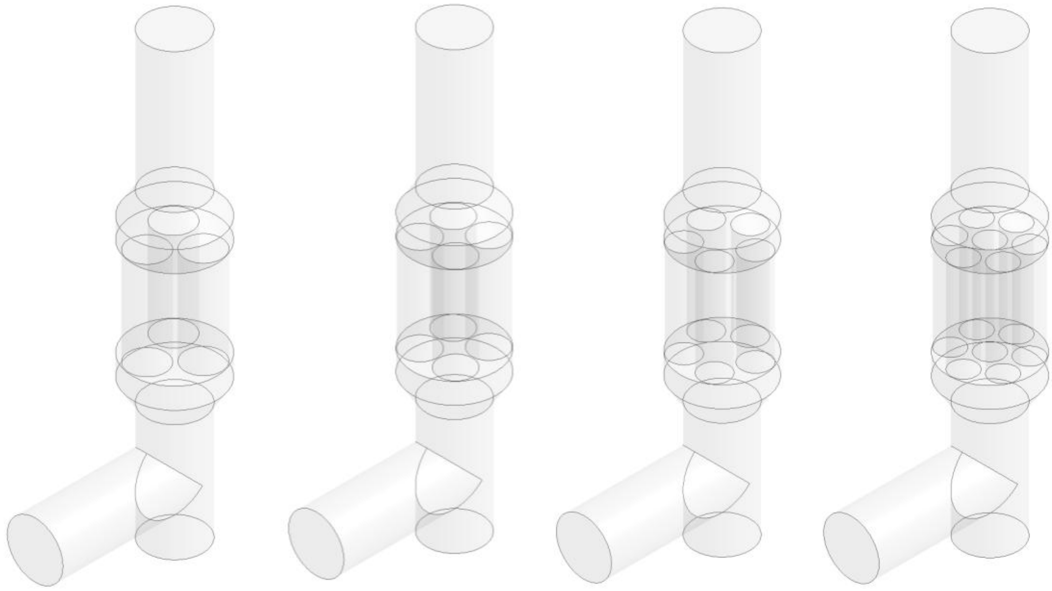

Fig. 1. Multi-tubular precipitator models: 3-tubular, 4-tubular, 5-tubular and 7-tubular

The mesh of the models is illustrated in Fig. 2. The predominant element shape across all configurations was tetrahedron. Table 1 provides details regarding the element number and average values of orthogonal quality and skewness. According to the data presented in Table 1, the mesh quality was deemed satisfactory in relation to established criteria for all proposed scenarios. The number of elements was in the range from 199940 to 230087. The orthogonal quality was approximately 0.79 which means it was very good and the skewness was approximately 0.20 which means it was excellent.

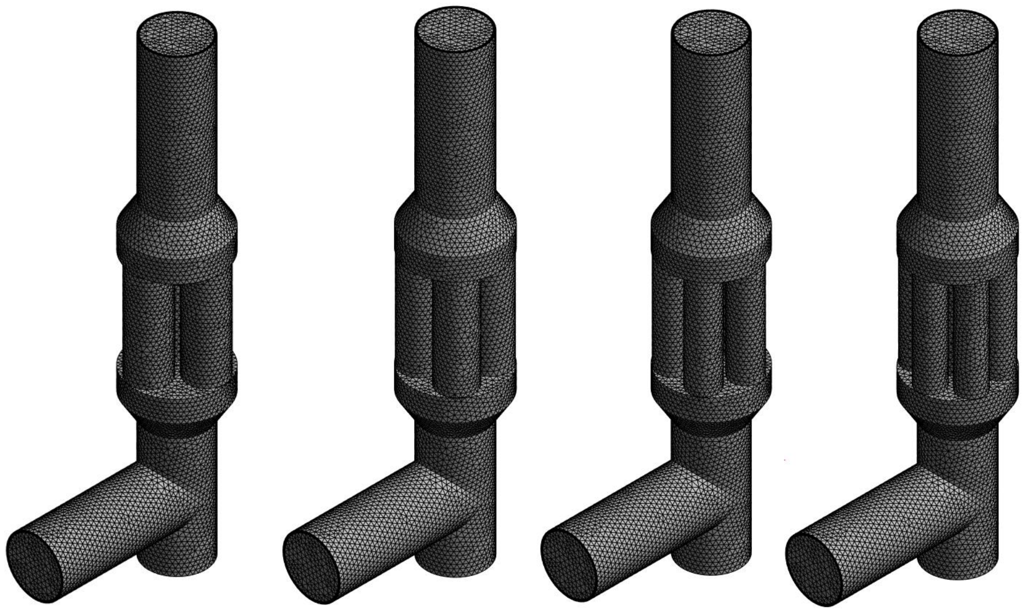

Fig. 2. Mesh of multi-tubular precipitator models: 3-tubular, 4-tubular, 5-tubular and 7-tubular

Table 1
Quality of mesh

| Number of | | Average values of | |
|---|---|---|---|
| **Tubes** | **Elements** | **Orthogonal Quality** | **Skewness** |
| 3 | 199940 | 0.795 | 0.203 |
| 4 | 209887 | 0.794 | 0.204 |
| 5 | 208443 | 0.791 | 0.207 |
| 7 | 230087 | 0.784 | 0.214 |

Two boundary conditions were set: mass flow rate at the inlet and pressure at the outlet. The mass flow rate of 0.0356 kg/s was calculated from the velocity measured by an anemometer during solid fuel combustion. The outlet pressure drop of -12 Pa was applied according to the standard *STN EN 13240*. Simulation of particulate matter motion in the flue gas was conducted using a two-phase model. Airflow was modeled using the Navier-Stokes equations. Lagrangian particle tracking was employed for particle motion. Equation (1) represents the Lagrangian particle tracking model used to simulate particle motion.

$$\frac{du_p}{dt} = F_D\left(u - u_p\right) + \frac{g_x\left(\rho_p - \rho\right)}{\rho_p} + F_x \quad (1)$$

The quantities in Equation (1) are as follows: $F_x$ is an additional acceleration, $F_D$ is the drag force, $u$ is the fluid velocity, $\rho$ is the fluid density, $u_p$ is the particle velocity, and $\rho_p$ is the particle density (Kantová et al., 2021).
The simulation employed the SST k-omega model, excluding the combustion process.

## 3. RESULTS

The increase in collection area, magnification of the collection area compared to a single-tube separator, and unused available space are presented in Table 2. Models with 4 and 7 tubes have approximately the same amount of unused space. The increased collection area is similar for 4-tube and 5-tube models, but the largest is for the 7-tube model.

Table 2
Volume comparison of multi-tubular precipitator models

| **Tubes** | **Area ($m^2$): Collection area** | **Magnification of the collection area** | **Volume ($m^3$): Unused space** |
|---|---|---|---|
| 3 | 0.4288 | 1.3 | 0.0108 |
| 4 | 0.5278 | 1.6 | 0.0089 |
| 5 | 0.5498 | 1.7 | 0.0110 |
| 7 | 0.6927 | 2.1 | 0.0092 |

Velocity distribution is shown in Fig. 3 with the size range of velocity from 0 to 2 $m \cdot s^{-1}$. The figures below the velocity profiles in Fig. 3 show the cross-section locations of the models for which the velocities are depicted. Based on the velocity distribution, it can be concluded that the flue gases flow through the individual tubes non-uniformly. Flue gas entering the main exhaust chimney pipe, impinges on the wall and subsequently flows predominantly along this wall, which is graphically manifested by higher velocities.

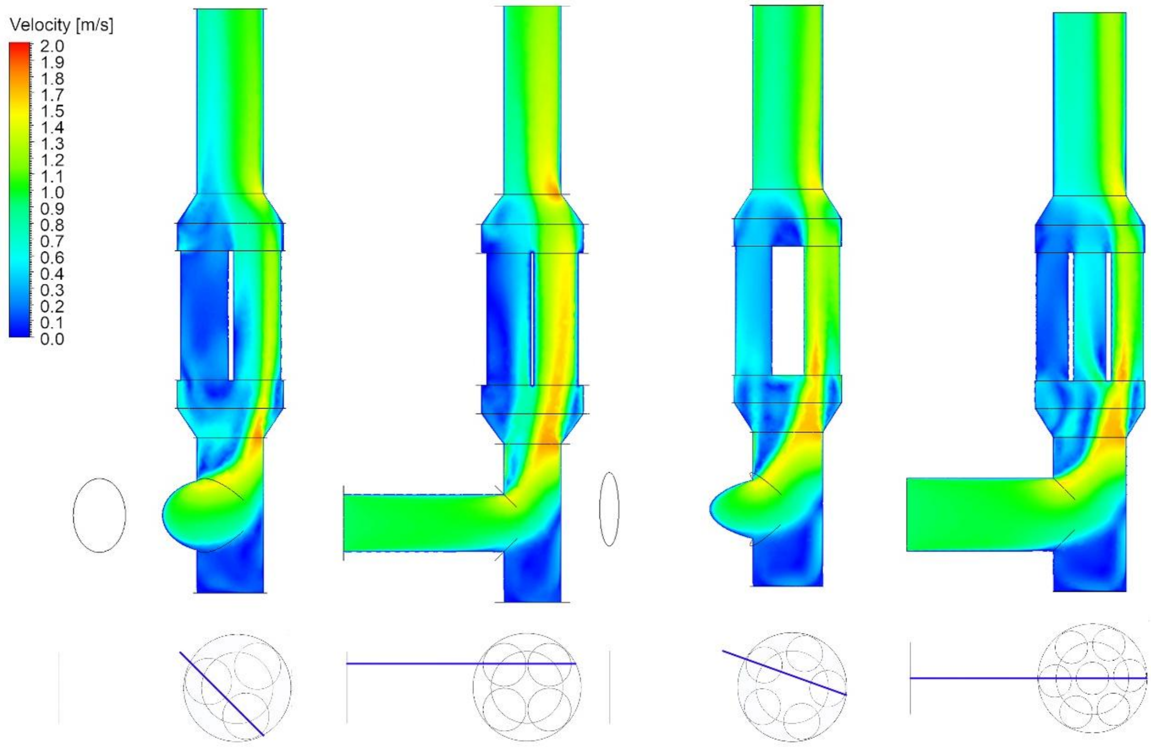


Fig. 3. Velocity distribution of multi-tubular precipitator models: 3-tubular, 4-tubular, 5-tubular and 7-tubular

Table 3 provides average values of velocities ($v_1$-$v_7$) in the individual tubular models. The results of the average velocities confirm the non-uniformity of the flow. For uniform flow, it would be appropriate to seek a suitable solution for a flow straightener, which we will further investigate.

Table 3
Average values of velocity for multi-tubular precipitator models

| Tubes | $v_1$ (m.s$^{-1}$) | $v_2$ (m.s$^{-1}$) | $v_3$ (m.s$^{-1}$) | $v_4$ (m.s$^{-1}$) | $v_5$ (m.s$^{-1}$) | $v_6$ (m.s$^{-1}$) | $v_7$ (m.s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 3 | 0.186 | 1.154 | 0.914 | - | - | - | - |
| 4 | 0.249 | 1.157 | 1.025 | 0.253 | - | - | - |
| 5 | 0.335 | 0.358 | 0.957 | 1.178 | 0.943 | - | - |
| 7 | 0.198 | 0.371 | 0.963 | 1.150 | 1.154 | 0.399 | 0.460 |

## 4. DISCUSSION

The efficiency of an ESP is contingent upon its operational and design parameters. Among the design parameters, the ESP specific collecting area, calculated as the ratio of total collecting area A to flue gas flow rate, holds significant importance. The effective particle drift velocity, a paramount operational parameter of an ESP, is influenced not only by particle characteristics, including size and material properties, but also by ESP operating conditions (high voltage and electric current) and the composition and temperature of the gaseous medium. However, discrepancies often arise between calculated and measured results. The evaluation of particle drift velocity may not fully capture the impact of real-world phenomena within ESPs, such as electric wind and gas turbulence. Additionally,

interactions between particles and the gaseous medium should be carefully considered (Høgh Petersen, 1988; Molchanov et al., 2020).
When designing a multi-tube electrostatic precipitator, it is crucial to ensure uniform gas flow through the tubes with centered electrodes to facilitate even particle collection on all collecting areas. Additionally, high particle velocities should be avoided to prevent particles from being carried out of the stack with the flue gas, allowing sufficient time for capture. In this article, due to non-uniform flow distribution through the tubes, the flue gas velocities varied, with values ranging from 0.186 to 1.178 m. $s^{-1}$.
Eom et al. in their research stated that maximum particle collection efficiency was anticipated when the discharge and collecting electrodes were positioned at the top of the air cavity, where particle residence time was extended due to reduced airflow velocity. Operating the electrostatic precipitator with double wall facade at 12 kV with an inlet velocity of 0.5 m. $s^{-1}$ was projected to yield a peak particle collection efficiency of 92.8% (Eom et al., 2019).
Researchers like Ahmadi et al., Guo et al., Li et al., Skodras et al., Arif et al. have used CFD models to study electric field distribution, PM trajectories, numbers of trapped particles, and more. The simple numerical method using CFD was presented in this article through which flow of flue gases could be observed. Based on these results, the flue gas flow was non-uniform and therefore the flue gases that flowed through individual tubes had different velocities. For uniform flow, it would be appropriate to seek a suitable solution for a flow straightener, which we will further investigate.

## 5. CONCLUSION

Particulate matter emissions from the combustion of solid fuels in small-scale heating systems remain a pressing concern. This problem is exacerbated using inappropriate fuel types and combustion settings. This article focuses on enhancing PM capture efficiency via electrostatic precipitation. It seeks to expand the fundamental principle of the single electrode in chimney tubular precipitator to a configuration with multi-tubular precipitation chambers. Increasing the number of tubes from one to three resulted in 1.3 times an increase in the collection area. Further expansions to 4, 5, and 7 tubes led to increases of 1.6, 1.7, and 2.1 times, respectively. Another significant aspect was the velocity distribution within the individual tubes. The simple numerical method using CFD was presented through which flow of flue gases could be observed. Based on these results, the flue gas flow was non-uniform and therefore the flue gases that flowed through individual tubes had different velocities. Non-uniform gas flow prevents full utilization of the separator potential, thereby reducing its efficiency. Additionally, high particle velocities should be avoided to prevent particles from being carried out of the stack with the flue gas, allowing sufficient time for capture. In this article, due to non-uniform flow distribution through the tubes, the flue gas velocities varied, with values ranging from 0.186 to 1.178 m. $s^{-1}$. For uniform flow, it would be appropriate to seek a suitable solution for a flow straightener, which we will further investigate.

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