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Investigating migration velocity in the clinker cooler one stage electrostatic precipitator (made by ELEx, Hamon, and FLSmith Co.)

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Abstract

Cement industry is one of the most important industries which plays a significant role in the development and prosper-ity of any country and worldwide. On the other hand, cement factories are among the major environmental plights and source of contamination. Accordingly, one of the main complications associated with these factories is controlling and preventing excessive emission of contaminants. Electrostatic precipitators are among the most important devices for controlling air pollution. One of the most important influential parameters affecting the efficiency of dust collection in the design of the electrostatic precipitator is the migration velocity. In this research, this parameter was studied in the electrostatic precipitators of ELEx, Hamon, and FLSmith companies, which are responsible for collecting the dust from clinker coolers in cement factories. The results of the study suggested that the range of this parameter under the men-tioned conditions was obtained as 8.7-11.5 cm/sec. Also, it can be stated that higher efficiency of the precipitator can be achieved by increasing the efficiency of mechanical dust collection. This can be realized by properly reducing costs, increasing the service life of equipment, and preventing environmental pollution.

Keywords: Cement industry, Modeling, Deutsch-Anderson equation, Migration velocity.

1. INTRODUCTION

The rapid advances in human societies over the past decades have resulted in fast development of steel, cement, and other industries. This progressive and indiscriminate development in different industries has led to production and emission of hundreds of contaminants with high contamination potentials. The amount of these contaminants is growing so fast that they can cause environmental issues [1]. Cement is one of the most important industries with a significant role in the advancement and prosperity of any country, and especially Iran as a developing country. Nevertheless, in spite of the need for cement and its development, it is considered as one of the industries with highest contamination [2]. Cement factories are regarded as considerable environmental contamination plights. Accordingly, one of the major issues of these factories is controlling and preventing excessive emission of contaminants. The most important and major contaminant associated with this industry is dust [3]. Electrostatic precipitators are among the most important devices for controlling air pollution, and are widely used in industries related to particulate matters such as cement and metallurgy industries. Electrostatic precipitators benefit from electrostatic force to separate dust particles from polluted gases. In air pollution control devices, low pressure drop is one of the important parameters and is considered an important advantage of electrostatic precipitators, mainly because it results is lower costs [4]. Over the past several decades, electrostatic precipitators have established their usefulness in cement and lime factories. It can be stated that this type of dust collector is a reliable equipment in preventing emission of dust to the atmosphere. Nevertheless, this kind of filter has a high efficiency as long as it is new, and once it undergoes wearing, its efficiency diminishes [5]. Industrial use of electrostatic precipitators or electric filters with the aim of further controlling dust pollutants dates back to the early 1950s. By improving the clean air law amendments in the US in 1970, use of electrostatic precipitators or electric filters developed considerably [1].

1.1. HISTORY OF ELECTROSTATIC PRECIPITATORS

Historically, the systematic background of use of electrostatic force for absorbing particles dates back to 600 B.C. and observations of Thales. He observed that when an amber rod is rubbed against wool objects, it is able to absorb the micro particles around it. Centuries later, scientists such as William Gilbert in 1600 and Stephan Gray in 1732 tried to systematize the electrostatic theory. In subsequent years, the novel theory of electrostatics was developed by Faraday and Coulomb. Considering its application in 1828, they claimed that the constituent particles of fume can be separated by an electric field. The principles of this phenomenon were restated in 1850 by Gitard, and similar experiments were performed in 1862 and 1878 by Gogin and Narold. In 1882-1886, Sir Oliver Ludge, an English scientist, developed the principles of precipitation of solid particles by electric field. A German scientist called Karl Muller separately made an

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electric filter and patented it under his own name in 1884 in Germany. In 1906. Frederick Gardner Cottrell. an American scientist, presented his scientific and applied solution for synthesizing electrostatic precipitators. In 1907, the first electrostatic precipitator made by him was successfully used to control mist drops of sulfuric acid from output gases of factories, whereby 5000 m³/min of gas was filtered by it. In 1919, the Lurgi Company came into existence to produce electrostatic precipitators and other air pollution control equipment. Today, the major application of electrostatic precipitators worldwide is found in power generation factories to contain coal ash, metal and iron melting factories, industries for burning wastes, cement factories, and other industries. Meanwhile, in Iran, cement factories are the main users of electric filters [6].



Fig. 1. The general schematic of an electrostatic precipitator

In the design and fabrication of electrostatic precipitators, successful manufacturer companies such as ELEx, FLSmith, and Hamon Research-Cottrell consider some details as classified technical information, and thus do not present them easily to other factories. One of these important points, as will be presented further, is the migration rate of particles. Different manufacturers usually consider a specific range of this parameter for different industries. Therefore, in this paper, By employing the governing equations and applying both theoretical and numerical calculations, the migration velocity of interest by the designer in the electrostatic precipitators made by ELEx, FLSmith, and Hamon Reseach-Cottrell were examined in three electrostatic precipitator system samples, which are responsible for collecting the dust of Clinker cooler, based on the design technical information in cement factories. The general schematic layout of an electrostatic precipitator is demonstrated in Fig. 1.

1.2. LITERATURE REVIEW

Electrostatic precipitators are used for clearing the gas at any stage of cement production. Most electrostatic precipitators have been made for 15 years of operation, and their function deteriorates with operation time. Precipitators separate dust from the output gas flow by around 99.9% or even higher [7]. Many researchers have examined the extent of collection of dusts by electrostatic precipitators. In 1999, Kim et al. [8] tested the efficiency of electrostatic precipitators to collect 0.1-100 um dust particles and achieved suitable results. They found that with reduction in the diameter of wire and wire-plate distance, the electrostatic precipitator efficiency increases. On the other hand, with elevation of the input air flow rate, the removal efficiency of particle decreases. In 2001, Kim et al. [9] presented a theoretical model for the efficiency of electrostatic precipitators for a distribution of particle sizes. In 2000, Zhuang et al. performed a theoretical and experimental study on the behavior of micro particles in electrostatic precipitators [10]. They calculated the separation efficiency of electrostatic precipitators that was in accordance with experimental data. In 2006, Skodras et al. modeled the removal of particles by an electrostatic precipitator with the help of computational fluid dynamics and concluded that the efficiency of the device improves with increasing wire voltages of and decreasing input gas flow rates (increased retention time), [11]. In 2012, Heydarbeig et al. investigated and analyzed pressure drop in electrostatic precipitators with the help of computational fluid dynamics. They observed that the pressure drop of this equipment is independent of particle size, and increases with flow rate [4]. The studies by Razavi Kermanshahi stated that one of the important points affecting dust collection efficiency of electrostatic filters is the frequency of the shock-inducer, which indirectly influences the migration velocity of particles [12]. The theoretical and empirical research by Keshavarz and Sedighina on improving electrostatic precipitator efficiency suggested that the increase in the cooling tower efficiency in cement industries has a direct effect on improving the dust collection efficiency of the electrostatic precipitator [13]. In their research on output concentration of the chimney of an electrostatic precipitator sample, Nezamparvar et al. [3] showed that the collecting efficiency of the system was 99.99% in the first year of operation. However, after eight years of operation of the mentioned system, its collecting efficiency dropped to 99.2%. Researchers have also investigated five samples of ELEx electrostatic precipitators under the combined condition of furnace and mill of raw materials. They calculated the migration velocity for the filters of this manufacturer as 10.63-15.76 [14]. In 2018, researchers reviewed various configurations of two-stage electrostatic precipitators, comprising a precharger and/or agglomerator in the first stage, and an electrostatic collector in the second stage [15]. In 2019, Liab et al. [16] studied the relationship between the ESP index and ESP performances. They defined the performance index predicted the collecting efficiency of ESP.

Researchers found that the optimal operating temperature for LLT–ESP is ~90 °C [17] in 2018. In another study, the balance between particle collection and re-entrainment was examined and a closed-loop electrostatic precipitator system was designed [18]. Collection efficiency of two-field and two-stage ESPs was compared by Jaworek and colleagues in 2018 [19]. Researchers concluded that the dust collection power of an electrostatic precipitator is heavily dependent on the following factors [5]:

- the humidity inside the gas
- chemical composition of the gas
- granulation distribution of particulate matters inside the gas and its chemical composition
- the electrical conductivity of particles
- temperature of gas
- type of the second fuel consumed (rubber-wood, etc.)

2. MATERIALS AND METHODS

2.1. PERFORMANCE MECHANISM AND ELECTROSTATIC PRECIPITATOR PURPOSE

The available electrostatic precipitators in the industry have various pathways for passage of gas flow, through which the gas passes at a rate of (usually) about 1 m/s. The paths consist of two rows of parallel vertical plates (collecting electrode) and a number of discharge electrodes [20]. The discharge electrodes are located vertically between the collector plates as suspended (without attachment to the ground). The function of electrostatic filters is developing a strong force in a fixed electric field on the particles inside the gas under treatment [6] that have been suspended as alternate rows with a pre-calculated distance (125-200 mm) from the top. Then, an electric potential with high voltage in direct-current is applied to the discharge and absorbent electrodes. The discharge electrode has negative polarity, while the collector electrode has positive polarity due to connection to the Earth. In response to this voltage, an electrostatic field with negative polarity is developed around the discharge electrode. The power of the field around the discharge electrode has the maximum intensity, and as by approaching the collecting electrode, the field becomes weaker. The region around the discharge electrode is the space in which the dust particles become charged [21].

The voltage applied to the discharge electrodes increases until the occurrence of the corona discharge, which can be observed as a blue luminous halo around the mentioned electrodes. The electrons freed by corona are highly accelerated in the current electric negative field (due to electric field repulsion), and move away from the discharge electrode. This acceleration results in high-intensity collision of free electrons to gas molecules, whereby they change into positive ions by losing one electron. The stages of gas ionization using the corona phenomenon have been shown in Fig. 2. As can be seen in this figure, this process continues recurrently which is called avalanche. Multiplication (the third part of Fig. 2) [21].



Fig. 2. The stages of gas ionization using corona phenomenon in the electrostatic precipitator [21]

With generation of positive gas ions, the ionized molecules are absorbed by the discharge electrode (negatively charged). Gas molecules are hundreds of times larger than electrons and move slowly, though these molecules can accelerate. Note that most of them directly collide with discharge electrodes or the gases around the discharge electrode, causing more electrons to be emitted from gas molecules. This phenomenon is called secondary emission, which is the second phenomenon that occurs. In the region between the discharge electrode and collecting plates, due to severe collision of the separated electrons with gas molecules, they are absorbed by them, causing production of negative gas molecules. In this state, due to the negative charge of gas molecules, they tend to move in the opposite direction of the negative field. For this reason, they move away from the field and towards the collector plate [21].



Fig. 3. The dust particles being charged following gas ionization with development of corona phenomenon [21]

The way dust particles become charged following gas ionization with the development of the corona phenomenon is shown in Fig. 3. Dust particles in the gas flow and on their way collide with negative ions. Gas ions attach to dust particles and make them negatively charged. However, most particles in comparison to gas molecules are larger. Nevertheless, gradually (in relation to the surface of guest particles). more gas ions can lie on particles. Smaller particles (diameter less than 1 micron) can absorb around 10 ions, while larger particles (diameter larger than 10 micron) can absorb tens of thousands of ions. Eventually, most of the gas ions attach to particles, and the particles emit negative electric charge. When this happens, the electric field around the particles causes rejection of ions. Larger particles are absorbed by the collector plate due to absorption of more ions and thus, with greater force. In other words, these particles are absorbed by the collector plate at a higher rate compared to smaller particles. Irrespective of the size, they collide with the collecting plate and attach to it (adhesive and cohesive forces). Eventually, negatively charged dust particles are discharged using the powerful negative electric field around the discharge electrode, and are absorbed by the positive collector plate. The effects of electrostatic field around each particle are demonstrated in Fig. 4. The absorbed particles gradually accumulate and form a dust layer (cake) until this layer of the collecting plate is transferred to the hopper by the shock-inducer system [21].



Fig. 4. The effects of electrostatic field around the particle (a) charge free particle b) charged particle [11]

Based on application, electric filters are categorized into two groups: one-stage and two-stage configurations. In the first type, the particles are charged and separated in one stage and concurrently; whereas in the second type, first the particles are charged and then after moving through plates, which are positive and negative alternately, absorption happens. These electrostatic precipitators have two power supplies. In the one-stage configuration, the discharge electrode has negative potential charge whereby electron is produced in the corona region. These electrons generate negative ions in the next stage, whereby the particles become eventually negatively charged. In two-stage electrostatic precipitators, the discharge electrode has positive charge, and thus in the corona region of these electrostatic precipitators,

positive ions are produced, which charge particles in the next stage. Clearly, due to the faster speed of electrons in moving towards the collector plates, onestage electrodes have greater efficiency, and accordingly one stage electrostatic precipitators are mostly used in the industry, but they have the disadvantage of ozone gas production in the corona region [6].

2.2. GOVERNING EQUATIONS

The main equation used in designing electrostatic precipitators is known as the Deutsch-Anderson equation first proposed in 1922 [1]. Figure 5 demonstrates the volume of gas control for the mass balance and obtaining the efficiency of an electrostatic dust collector. As illustrated in Fig. 5, the gas moves along the x direction and parallel to the surface of the precipitator. On the other hand, the suspended particles move perpendicular to the gas flow under the influence of electric field towards the collector plate.

If the law of conservation of particles is written in the distance X, within the length of a control volume Δx and length of W and distance between the two precipitator plates, the following equation is obtained:

$$V_{g}.S.H.C_{X} = V_{g}.S.H.C_{X+\Delta X} + 2H.\Delta X.W.C$$
 (1)

Where V_g is the gas flow rate and particles with speed W move towards both plates located at both sides of the charge donating electrode. C represents the concentration of particles in the gas. It has been assumed that due to the turbulence of gas flow in the control volume, the concentration of particles is homogeneous. After differentiation of Eq. (1), the following equation is obtained:

$$-dC/C = (2H.W) .dx /(S.H.V_g)$$
(2)

After solving Eq. (2), Eqs. (3) and (4) are obtained:

$$Ln(C_0/C_1) = -2S . W . L/(S . H . V_g)$$
 (3)

$$(C_0 / C_1) = \exp(-A . W / Q_g)$$
 (4)

Hence, the Deutsch-Anderson relation can be written as Eq. (5):

$$\eta = (C1 - C0) / C1 = 1 - \exp(-A . W/Q_g)$$
(5)

In the above relation, η is the equipment efficiency, W is the particle absorption rate (m/sec), A if the total effective surface area of the collector plates (m²) and Q_g is the gas volumetric flow rate (m³/sec).

Therefore, by inversing Eq. (5), the migration velocity can be obtained by Eq. (6):

$$W = -\ln(1-\eta) Q / A$$
 (6)

Equation 5 is the outcome of several years of endeavor of designers and researchers for representation of accidents and necessary predictions in an electrostatic precipitator, all of whom have consensus over this relation in that it is simple and at the same time the most important and practical formula to calculate the efficiency of electrostatic precipitators. Although this relation seemingly does not have any terms associated with electric field, charge of particles, and intensity of the applied current, the effect of all these factors on efficiency has been incorporated in the limits rate of the particles. Therefore, determining the limits rate of the particle is one of the most important parts of design or the foundation of designing electrostatic precipitators, and can be calculated using the presented equations [5, 6, 22]. The effect of migration velocity on the amount of dust in the output dust of the filter, which represents the importance of this parameter in the efficiency of dust collection, is shown in Fig. 6.

3. RESULTS AND DISCUSSION

This section deals with the case study of migration velocity (by designer) in three electrostatic precipitator system devices of one stage type designed by ELEx, FLSmith, and Hamon Research-Cottrell companies. Table 1 presents the properties of the mentioned electrostatic precipitators. Note that the specifications of the above-mentioned filters (installed across different cement lines) are responsible for collecting dust from the clinker cooler.



Fig. 5. The gas control volume for the balance [14]



Fig. 6. The effect of migration velocity on the amount of dust present in the output dust of the filter [14]

Table 1. The properties of the studied electrostatic pr	recipitators
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Supplier	Unit	ElEx1	FLSmith ²	Hamon 3
Volume Flow	m ³ /s	131.6	141.7	133.9
Filtration Area	m ²	9072	7560	8820
Efficiency	%	99.75	99.72	99.95

According to the Deutsch-Anderson equations mentioned earlier, the values calculated for the particle migration velocity (related to the electrostatic precipitators in Table 1) considered in the design are according to Table 2.

 Table 2. The results calculated for migration velocity in the studied electrostatic precipitators

Supplier	Unit	ElEx	FLSmith	Hamon
Volume Flow	m ³ /s	131.6	141.7	133.9
Filtration Area	m ²	9072	7560	8820
Efficiency	%	99.75	99.72	99.95
Migration Velocity	cm/s	8.7	11	11.5

Note that in the electrostatic precipitators, in addition to separation under the influence of the applied electric field, part of the dust particles precipitates under the influence of gravity or due to collision and deviation. When the energy supply is disconnected or power outage occurs in cement factories, the electrostatic precipitator operates as a precipitation chamber with an efficiency of around 30-70%. Therefore, by having the initial concentration of dust and considering the minimum efficiency of mechanical dust collection of the device (30%), it can be stated that the migration velocity is lower than the above values [6].

4. CONCLUSION

Study and analysis of information and the technical properties of the electrostatic precipitators in different cement factories help researchers to gain better awareness about the current equipment and thus they can take steps to localize and generate knowledge in different areas especially the equipment associated with environmental pollution prevention. In this study, the parameter of the migration velocity of particles was studied in the electrostatic precipitators made by ELEx, FLSmith, and Hamon Research-Cottrell companies, which are responsible for collecting dust from clinker coolers in different cement factories. The results suggested that the mentioned factories have considered 8.7-11.5 cm/sec as the migration velocity of particles in their electrostatic precipitators used under the mentioned conditions. Nevertheless, it can be claimed that with elevation of the mechanical dust collection efficiency of the system, the desired dust collection efficiency can be achieved at a lower migration velocity. This can be fulfilled with proper exploitation

¹⁻ ELEX AG (Electrical Extraction) was founded in 1934 and is a Swiss family-run company with branch offices in India, China and Germany.

²⁻FLSmidth & Co. A/S is a global engineering company based in Copenhagen, Denmark. With almost 11,700 employees

worldwide, it provides global cement and mineral industries with factories, machinery, services and know-how.

³⁻ Hamon Research-Cottrell GmbH was founded by the brothers Achille and Fernand Hamon. Its industrial activity started at the very beginning of the 20th century and developed the cooling tower business.

of chemical, mechanical, and electricity engineering as well as the experiences of scholars, thus reducing the costs, water consumption in the cooling tower, and improvingthe dust collection efficiency. Also, by investigating the guaranteed efficiency and migration velocity of the ELEx and FLSmith electrostatic precipitators, it is probable that the mechanical dust collection efficiency of ELEx electrostatic precipitators would be superior to that of the other electrostatic precipitator.

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