Energy xxx (2016) 1–10

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance of a lab-scale tubular-type electrostatic precipitator using a diesel engine particle emission source

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ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form
26 February 2016
Accepted 4 March 2016
Available online xxx

Keywords:
ESP (electrostatic precipitator)
Experimental
Emissions
Particles
Collection efficiency

ABSTRACT

Air pollution is a topic currently studied to address the well-known health problems that can arise from it. The use of an ESP (electrostatic precipitator) for treatment with submicron particles from sources such as small-scale combustion systems presents some advantages in comparison to other possible devices. In this study, a new ESP prototype geometry based on separating the discharge electrode support from the gas stream path was designed, constructed and tested. The gas stream from a small-size diesel internal combustion engine was used. Good ESP behavior over moderate time periods was verified by achieving average collection efficiencies of 97 ± 4%. TG (Thermogravimetric) and SEM-EDS (Scanning Electron Microscopy with Energy Dispersive X-Ray Spectroscopy) analyses were performed. The influence of the regulation power value and the discharge electrode effective length on the collection efficiency was evaluated. Higher removal efficiencies were linked to higher power values and higher discharge electrode effective lengths. A high impact of the operating time was observed. Different discharge electrode geometries were tested, indicating an increase in collection efficiency as the power increased for stainless steel electrodes and the opposite trend for M12 threaded rod electrodes.

1. Introduction

Based on the previously recognized relevance that small-scale combustion systems are linked to air pollution and particle emissions as well as its implications for human health [1,2], the use of particle control systems has emerged [3]. Although there exists a wide variety of devices for this purpose [4,5], ESPs (electrostatic precipitators) seem to be one of the most suitable options [6–9]. Among its advantages, Bordado et al. [9] identified a relatively low pressure drop, high removal efficiencies, the possibility to handle gases with high moisture content and an easy separation and recovery of collected solids.

ESPs base their operation on the application of electrostatic forces to collect airborne particles, thus removing them from the gas stream. One or more discharge electrodes are placed between two collection plates or held in the middle of a cylinder, resulting in plate or tubular ESPs, respectively. An electric field is created by applying a high voltage to these discharge electrodes, producing gaseous ions that collide with the gas stream particles, thus charging them by field or diffusion mechanisms. Once charged, these particles migrate to the collection surfaces where they can be removed periodically [10].

As expected, collection efficiency is one of the most studied parameters when analyzing ESPs behavior, both experimentally and numerically. Porteiro et al. [11] developed a computational model validated against experimental data from the literature, where the theoretical collection efficiency is computed as a function of particle diameter. Li et al. improved the ESP collection efficiency reducing the gas temperature by using a low-pressure economizer [12]. Kim et al. [13] evaluated experimentally the ESP performance. In addition, these results were compared to those obtained from the Deutsch's collection theory.

After several decades, current research continues to study different aspects of increasing the removal efficiency of electrostatic precipitators. Some of these studies address the remaining unsolved problems in this field, including back-corona discharge, submicron particle removal and particle re-entrainment [14]. Back corona results when the potential difference at the surface of the dust layer accumulated in the collection electrode is high enough to cause the particles to break down [15], a phenomenon that can be caused by high resistivity dust [16]. Several studies have attempted to address this challenge in different ways. Among others, Majid et al. [17] measured the electrical resistivity of the gas using a laboratory setup in which the onset of back corona was detected and could be

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http://dx.doi.org/10.1016/j.energy.2016.03.067
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Nomenclature

b_{eq}	equivalent mobility (m^2/V s)
C	particle concentration (mg/m^3)
E_c	critical value of the electric field at the wire surface (V/m)
K_{ext}	extinction coefficient (m^{-1})
i	current per unit length (A/m)
r_w	discharge electrode radius (m)
R	ESP radius (m)
V	wire voltage in the ESP (V)
V_c	corona inception voltage (V)

Greek symbols

ε_o	electric permeability of the medium (F/m)
η	removal efficiency (%)

Abbreviations

CF	fixed carbon
COC	condensable organic compounds
DT	dead time
ESP	electrostatic precipitator
PM	particulate matter
SEM-EDS	scanning electron microscopy with energy dispersive X-Ray spectroscopy
TGA	thermogravimetric analysis
WD	working distance

eliminated by reducing the current by controlling the supplied voltage. In addition, the presence of back corona aggravates particle re-entrainment [18]. Ni et al. [19] studied the development of back corona discharge in a wire-cylinder ESP. They classified the discharge process after back corona into different stages. Additionally, they proposed a physical model to explain the processes that initiate, maintain and develop back corona discharge. Blanchard et al. [20] focused their investigation on layer formation and re-entrainment of particles, where they identified a strong correlation between the current density distribution on the collection plates and the dust layer pattern as well as two modes of growth and packing for the layer. Yamamoto et al. [21] observed the particle re-entrainment after a rapping process using the laser light sheet technique, and the surface profile of the dust layer was measured. Zukeran et al. [22] concluded that there exists a dependence between particle re-entrainment and gas flow velocity. Mizuno et al. [23] described the causes of these phenomena and how to handle them. Injection of adhesive agents, wet ESP or alternative rapping could eliminate re-entrainment of particles. To cope with the appearance of back corona, various methods were proposed, such as mechanical scraping or brushing, variation of temperature and humidity, intermittent or pulse energization, etc. The use of a two-stage ESP to coagulate fine particles is suggested to increase the collection efficiency of submicron particles. Niewulis et al. [24] studied the influence of the EHD secondary flow generated in a narrow wire cylinder-type ESP on the submicron dust particle collection efficiency by concentric and non-concentric configurations. The turbulence appeared to be one of the originating factors in addition to ESP electrode geometry and operating conditions.

A suitable ESP design remains a current investigation theme to improve the collection efficiency and attempt to avoid some of the aforementioned issues. This work continues a previous study on a lab-scale tubular-type ESP prototype designed, constructed and tested at the University of Vigo, which described the preliminary attempts to develop particle control equipment to be installed in a domestic pellet boiler [25]. The architecture of the former ESP prototype led to the observance of some problems during its operation. The gas stream crossed all the internal surfaces of the prototype, including the discharge electrode support structure. Both the temperatures achieved and the inorganic fouled matter caused this surface to become slightly sticky and therefore airborne particles tended to accumulate in this region. After a certain period of operation (less than 10 min in the worst case), particles accumulating on this structure created a layer that allowed for a current pathway between the discharge and collection electrodes. Thus, the electric field became weaker and the collection efficiency decreased. At a certain point, the thickness of the deposited particles became large enough that all the current was discharged through it, preventing the corona inception. Once this fact occurred, the ESP stopped working, leading to very short operation times.

With the aim of solving this problem, a re-designed ESP was analyzed and developed in the current study. In addition, to obtain good device behavior and attempt to improve the removal efficiency, some novel parameters were studied, specifically the discharge electrode effective length.

2. Experimental facility

2.1. ESP prototype

Previous works have demonstrated that the central electrode fixation system cannot be placed in the combustion gas streamline [25]. With this in mind, the ESP employed in this work was consequently re-designed. Fig. 1 presents the resulting ESP after the re-designed process. The prototype has an inner diameter of 150 mm and a length of 1.7 m. The gas stream enters and leaves the main ESP body through 2 lateral conducts (135°). The discharge electrode is held and centered with two plates positioned at both ends of the system. Therefore, there is no continuous gas flow through the fixation system. Although some stagnant gas may be retained in those extreme areas because the atmosphere is not continuously renewed, the fouling process is prevented, increasing the lifetime of the equipment under service.

During the setup phase, different materials were tested for the fixation system, including methacrylate and wood covers. Finally, two transparent covers made from glass were selected through which the discharge electrode was held and centered. Using this transparent material, the process occurring inside the ESP can be easily observed. As shown in Fig. 1, the useless length of the electrode (stagnant gas part) may be insulated using two cylindrical glass covers. The corona inception in these areas can thus be avoided, reducing the current values registered for a certain applied voltage. The effective length is defined as the free discharge electrode length with a maximum value of 1.4 m.

The entire experimental setup consists of the ESP prototype, a wood supporting structure and a high voltage source (Fig. A of the Electronic Appendix). The supporting structure was developed according to the ESP design, guaranteeing the perfect centering of the discharge electrode fasteners as well as easy and safe handling of the device. The high voltage source used was from SPELLMAN and had a maximum output voltage of 50,000 V. The time off in response to arcs is 5 ms, with a maximum number of admissible arcs per minute of 24. The over current cutoff limit was set to 3 mA.

2.2. Diesel engine as particle emission source

A small-size diesel internal combustion engine from PERKINS with a nominal power of 9.5 kW was used as the particle emission