PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

OPTIMISATION OF REPLACEMENT INTERVALS FOR PULSE JET FABRIC FILTERS OF A COAL POWER GENERATION PLANT

GLORIA DEL PILAR LARA MARRO

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
RODRIGO PASCUAL

Santiago de Chile, Agosto 2016

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To my beloved son Sergio

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I'd like to thank my parents and siblings, my grandparents and my aunt Ceci with my uncle Sergio, for their support throughout this, not always beautiful, journey. My friends from UC, Andrea Spohr, David Godoy, David Peters and Felipe Pastene, without you guys, I wouldn't be writing this today. To my friends and coworkers in DUOC UC, Cristian Cavieres, Manuel Madariaga y Jaime Parra, for your constant support when times went difficult. I just want to tell you all... Thanks... and please don't ever let me do something like this again.

"The Lord is my shepherd, I lack nothing. He makes me lie down in green pastures, he leads me beside quiet waters, he refreshes my soul. He guides me along the right paths for his names sake. Even though I walk through the darkest valley, I will fear no evil, for you are with me; your rod and your staff, they comfort me." Psalm 23.

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ABSTRACT

Nowadays, pulse jet fabric filters are an alternative to clean flue gases from coal combustion. A filter failure generates uncontrolled emission of pollutants, which may force a power plant to shutdown with drastic economic and environmental consequences. This is the main reason to consider filters as critical components, despite their low cost. For pulse jet filters, high pressure air pulses must be released frequently to maintain a proper operation. Eventually, these pulses wear out the fibers, generating a failure. The objective is to estimate optimal replacement intervals for pulse jet filters considering its pulses and its effect on filter reliability and direct costs. This study considers an estimation of accumulated cleaning cycles which are included as a complementary time scale along with service hours, as a multiple time scale approach. Despite the number of studies performed, to the best of the authors knowledge, this analysis has never been reported before in filters. A case study of pulse jet filters from a thermoelectric plant was analyzed using this multiple time scale model for studying its reliability and effect on direct costs. Results show savings up to 38% in direct costs by modifying pulse frequency and avoid early replacements in addition to avoiding fines for not meeting environmental regulations.

Key Words: reliability, baghouses, multiple time scales, pulse jet, power plants, coal

RESUMEN

Uno de los desafíos de los sistemas de generación eléctrica en base a carbón es la reducción de emisiones de material particulado. Hoy en día los filtros de mangas pulse jet son una alternativa para limpiar los gases de la combustión del carbón. Una falla de filtros genera emisiones fuera de control lo que obliga a detener la planta, generando a su vez drásticas consecuencias económicas y medioambientales. Esta es la principal razón para considerar este tipo de filtros como componentes críticos, a pesar de su bajo costo. Para el caso de los filtros pulse jet, pulsos de alta presión deben descargarse frecuentemente para liberar el polvo capturado por ellos y mantener su apropiado funcionamiento. Este estudio muestra el efecto de la frecuencia de pulsos en la vida útil de los filtros de mangas desde el punto de vista de la confiabilidad. Este enfoque considera que los ciclos acumulados de limpieza se estiman y se incluyen como una escala de tiempo combinado junto a las horas de operación en el análisis de confiabilidad. De acuerdo a lo revisado por los autores, este tipo de análisis de tiempos combinados nunca se ha reportado antes en la literatura. El objetivo es estimar intervalos de reemplazo óptimos para los filtros considerando costos de mantenimiento y confiabilidad de los filtros. El modelo generado se probó en un estudio de caso de una termoeléctrica. Los resultados muestran ahorros de hasta 40% en costos directos al realizar reemplazos antes de tiempo. Además, al evitar fallas inesperadas se pueden ahorrar entre 20 y 30 mil USD por hora de detención, sin considerar las multas por no cumplir con las regulaciones medioambientales.

Palabras claves: confiabilidad, filtros de mangas, tiempos combinados, pulse jet, termoeléctricas

1. INTRODUCTION

Although renewable energies have been extended in recent years, according to Miller [2015] it is still expected that by 2040 the use of coal in power generation systems will reach 36% worldwide, 4% less than in 2010. Coal has many advantages as delocalization and low cost, but it also has a major disadvantage: pollutants emissions [Franco and Diaz, 2009], such as particulate matter, mercury and sulfur oxides [Miller, 2015]. Due to its physical characteristics, particulate matter is very harmful, especially particles smaller than 10 μm (PM10) or smaller than 2.5 μm (PM2.5), since they are able to reach deep within the lung wall [Upadhyay et al., 2014], and they may increase lung and heart diseases [Riva et al., 2011; Stanek et al., 2011].

In order to control these emissions, environmental agencies from all over the world have established regulations, which have encouraged the development of technologies focused on emissions control. According to the type of pollutant, there are different control processes. For example, desulfurizers minimise sulfur oxides released to the atmosphere, while electrostatic precipitators and fabric filters control fine particulate matter. Since 1970s, electrostatic precipitators have been the most used technology to control particulate matter thanks to its high efficiency, air processing volume, range of particle collection up to 0.5 μm and its ability to process gases at high temperatures [Miller, 2015]. However, as regulations have become more strict and difficult to achieve, bigger and more expensive electrostatic precipitators are required. In this context, fabric filters have become an attractive alternative to control fine particulate matter, alternative which continues to develop based on the new technologies available, as the one shown in Miller et al. [2002].

1.1. Thesis Scope

The development of this thesis has been possible thanks to an electrical generating company request to investigate certain aspects related to the operation of one of its new pollutant reduction systems, the fabric filters. These have been installed in two of their power plants and although they have been operating for a couple of years, they were unaware of whether the operating conditions were correct or if the faults they were experiencing were normal or even if improvements could be made. Initially, the development of this thesis would imply studying both the desulphurising system and the bag filters, but considering the amount of information and time available, after an agreement with the company, the study focused on the bag filters only. The research began with a bibliographical compilation, both from the same company as external (magazines, books, etc.). In addition, meetings were held between company central office staff, who were the most interested in the research, and the local office where the plant was located. Despite the numerous problems in order to collect information in the field, lack of will, lack of internal communication of the company itself and lack of historical information concerning filters, it was possible to have an idea of the operation of the system, parameters and general conditions of the maintenance of the filters. Three field visits were also carried out, one of which corresponded to a plant maintenance outage. From this visit the most operational information and local contacts were obtained to be able to continue working on the thesis. Unfortunately, over time the company lost interest; the lack of information of the filters and lack of interest of the local company made it increasingly difficult to continue the research and generating useful results, but contact with plant operators was maintained. This eventually led to change the investigation focus, becoming an study based on theory using real data collected in the field and others sent by plant operators. This thesis is the result of a practical and theoretical research, which presents conclusions applicable to other case studies that present systems of fabric filters. It also can be complemented with more finished studies of fuel types (coal, biomass, etc), operational and maintenance conditions.

1.2. Fabric Filters

Fabric filters have been studied since they were introduced in the market, in the 1970s [Carr and Smith, 1984]. Since then, diverse analysis, surveys and experiments have been

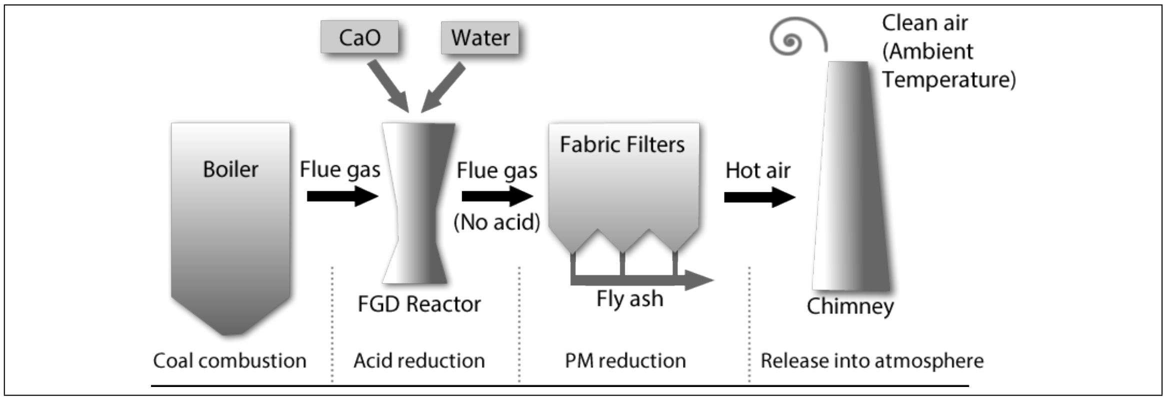

Figure 1.1. Power plant diagram with fabric filters collection system

developed, always focused on improving efficiency [Bustard et al., 1992; Hindy et al., 1987; Simon et al., 2007]. They have many advantages, like high collection efficiency (higher than 99%), large volume for gases filtering, the ability to capture particles as small as 0.01 μm and a design flexibility thanks to the different filtering media and cleaning processes [Miller, 2015].

When we talk about fabric filters, we refer to any element made of an specific type of fabric that it is use to block particulate matter. These type of filters can be found in several applications where fossil fuel combustion is produce, for example: foundries, biomass reactors, firing kilns and coal power plants. Usually are arrangements of fabric tubes in which flue gases laden with particles pass through them and collect those particles, releasing only clean air to the atmosphere. Fabric filter characterise not just by their capacity to capture small particles, but also capturing particles of any shape and any texture, allowing clean air pass through them. To fulfill their objective, fabric filters must be selected very carefully, considering several variables related to the combustion, as gas temperature and volume, pH, ash morphology, among others.

1.2.1. Capture mechanisms

There are two main mechanisms in fabric filters, to collect particles [Beachler et al., 1995]: impaction and interception. The first one affects to larger particles, because they have a bigger inertia, they are unable to keep in the gas stream therefore they impact the fiber of the filter and they stay there. Medium size particles tend to go with the gas stream, but they still have enough inertia to not stay in the stream, so instead of impacting the fiber, they graze it, been intercepted by the filter. In some cases, when particles are less than 1 μm, they tend to move in an erratic way responding to Brownian motion. Therefore, smaller particles can also be captured by the filter, despite their size.

1.2.2. Operation

There are two ways for fabric filters to operate which may be identified by how the exhaust gas enters the filters: with positive or negative pressure. Positive pressure implies fans pushing the gas trough the filters and in negative pressure, fans pull the gas trough them. To choose which is the best type of filter, it is necessary to consider gas particles characteristics as abrasion, moisture and how corrosive the gas is. Negative pressure filters are proved to have a better resistance to these conditions but they are also the most expensive choice.

1.2.3. Cleaning

For the first fabric filters, cleaning them implies to stop their operation every time needed. To minimize impact, filter are arranged in compartments or sections, which are isolated to be cleaned without affecting general operation. Exhaust gas is diverted to the others operating sections, making this cleaning method an intermittent one. On the other hand, with better technology, a continuous cleaning method was developed, where the filter, individually, is stopped from operation for a short period of time while an air pulse clean it. The pulse goes from one filter to another until all filters are cleaned, waiting to start again. For this method it is not necessary to arrange the filters in compartments, but it is still require for maintenance purposes.

Regarding to the cleaning mechanism, there are three different types that can be identify. First it is shaking, that can be apply manual or mechanically. It is an horizontal movement of low energy generated at the top of the filter. Exhaust gas enters the filter from the inside to the outside, capturing particles. Filters are shake to release dust cake formed on the inside of the filter. Their cleaning frequency depends on dust type, concentration and pressure drop across the filters [Beachler et al., 1995] and it last approximately 30 seconds per filter. It is not recommended to use this type of cleaning when dust collected is sticky, because its force can rip the fabric.

The second cleaning method is by reverse air. As its name indicates, it works through an air flow that goes against the regular exhaust gas flow. To be able to do this it is necessary to stop the exhaust gas flow of the filter to clean. To make this process easier, filters are grouped in compartments, which are taken off the process and cleaned them one at a time. As in shaking method, exhaust gas flows from the inside to the outside of the filter, letting clean air pass trough the fabric and capturing dust inside de filter. The reverse air flow, looses and collects the dust in a hopper to be disposed. For this type of cleaning, the filter is a tubular bag and must have inner rings to avoid filter collapsing. These rings are placed to equal distances depending on filter's length, every 0.6 to 1.2 meters [Beachler et al., 1995].

Unlike previous methods, pulse jet receives flue gases from the outside of the filter, capturing there exhaust gas particles and letting clean air passes through it. To clean them, a high pressure air pulse travels as a wave along the filter, inflating it and letting loose the external dust cake [Kitto and Stultz, 2015; Miller, 2015]. As previous cleaning methods, the filters are tubular bags made of a determined type of fabric. In pulse jet cases these bags have a metallic cage inside for support, because of the high pressure of the air pulsed (60 to 100 psi), filters are subject to deformations due to continuous pulsing. In reverse gas cases, a fan is used to provide the air flow necessary to clean the filters, which implies less pressure and more time to clean them all (1 to 2 min for each filter), versus pulse jet,

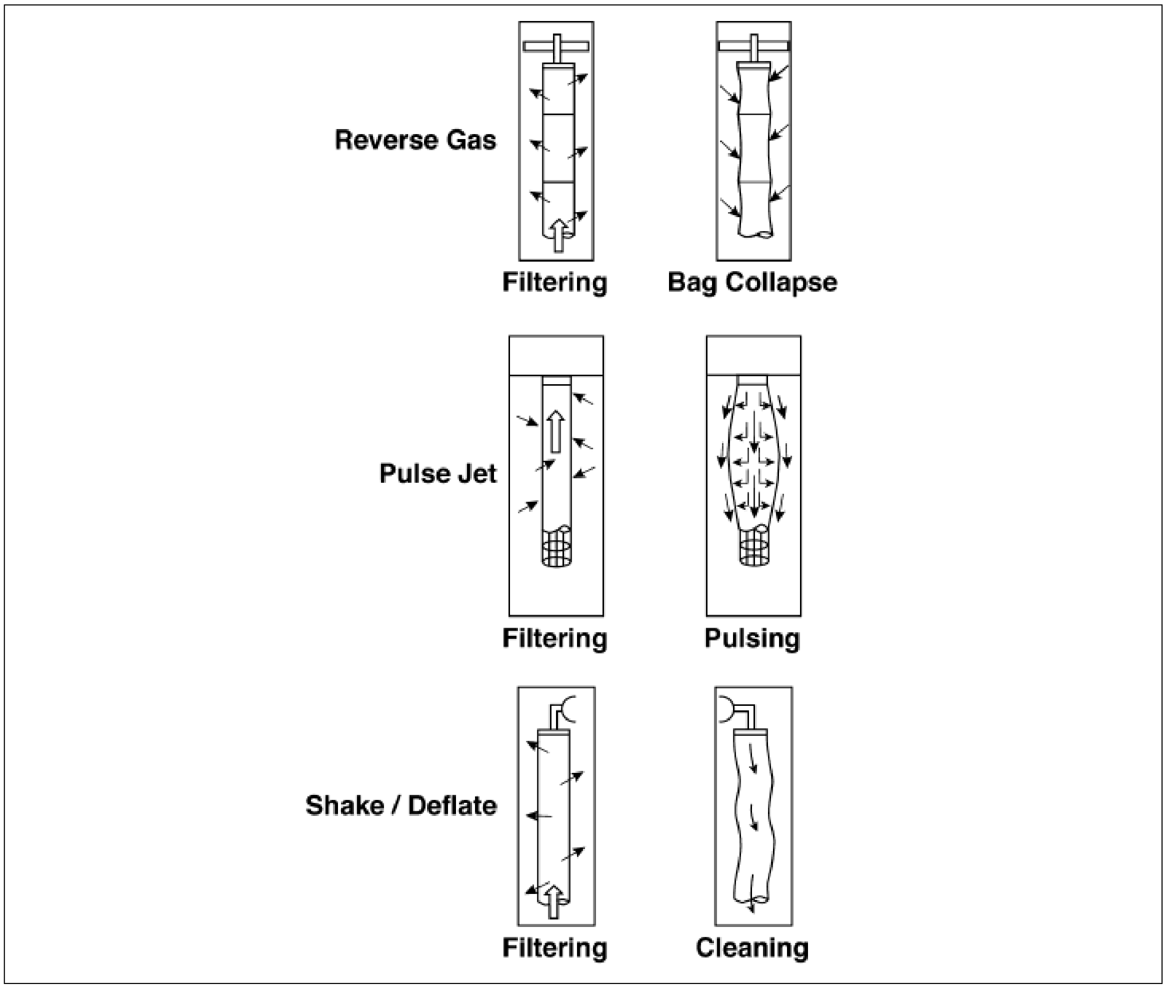

Figure 1.2. Fabric filters cleaning methods [Miller, 2015]

with a cleaning time of 0.1 seconds for each filter, a whole compartment can be cleaned in 30 seconds (depending on how many bags are per compartment).

1.2.4. Design

To design a fabric filter, there are three variables to take into account [Beachler et al., 1995]: pressure drop, filter drag and filtration velocity.

The pressure drop is the difference between the inlet and the outlet pressure. It ss how the resistance to air flow is measured. Pressure drop is the most important variable, it defines fan capabilities for exhaust gas and therefore energy necessities for the plant. It depends on dust cake and fabric characteristics. From Darcy's law, the equation 1.1 can predict total pressure drop across the dirty filter, adding the drop across the clean fabric to drop across the dust cake:

$$\Delta p_t = \Delta p_f + \Delta p_c \tag{1.1}$$

Where Δp_f is the pressure drop across the clean fabric (cm of H_2O) and Δp_c is the pressure drop across de dust cake (cm of H_2O).

To estimate total pressure drop, Equation 1.2 is used, where k_1 is the fabric resistance (cm $H_2O/(cm/sec)$), k_2 is dust cake resistance ($cmH_2O/(g/cm^2 - cm/sec)$), v_f is filtration velocity (cm/sec), c_i is dust concentration loading (g/cm^3) and t is filtration time (sec).

$$\Delta p_t = k_1 v_f + k_2 c_i v_f^2 t \tag{1.2}$$

Both k_1 and k_2, are coefficients determined experimentally and depends on exhaust gas viscosity, fabric and dust cake thickness, porosity and density. When the dust cake collected on the filter surface is thick enough, pressure drop will increase and reach certain limit. At this time it will be necessary to clean the filter with its air pulse jet. After that the pressure drop will decrease to operational levels.

The filter drag refers to the air resistance across the fabric and dust cake, but the latter is the most determining factor because as the dust particles accumulate, they block fabric openings, increasing the resistance rapidly. Filter drag depends on pressure drop and filtration velocity. It determines filter performance which it changes if there is a single bag or several bags in different compartments. Mathematically can be express as Equation 1.3, where Δp is pressure drop (cm H_2O) and v_f is filtration velocity (cm/sec) and S is the filter drag (cm $H_2O/(cm/sec)$).

$$S = \frac{\Delta p}{v_f} \tag{1.3}$$

In a single bag case, it is easy to identify the stages of dust cake formation observing its performance curve as in Figure 1.3. At the beginning of the curve, it can see the residual drag of the clean filter. Then, the curve grows constantly as the dust cake accumulates creating the dust cake.

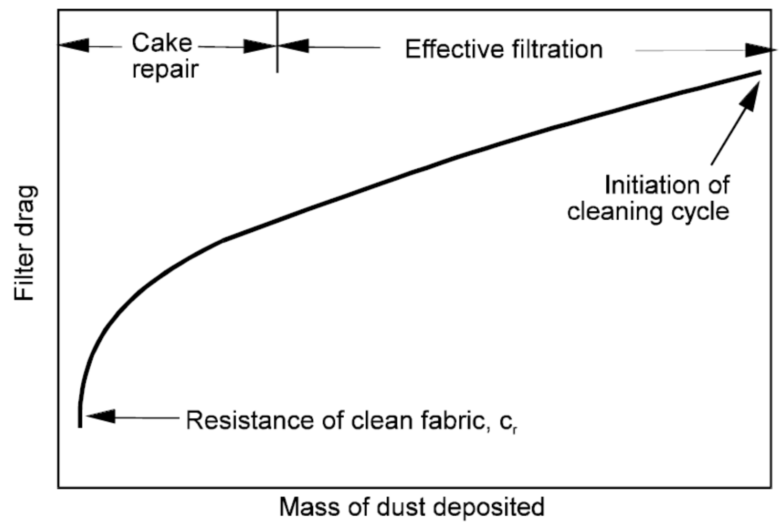

Figure 1.3. Performance curve for a single woven bag [Beachler et al., 1995]

On the other hand, when there are several filters ordered in different compartments and cleaned in a sequence, the performance curve changes, because it incorporates more filters in the analysis, as Figure 1.4 shows. It is possible to observe a stabilization time when the filter is cleaned and need to form for the first time its dust cake, as well as several cleaning cycles, generating a curve with a saw form, where the single bag curve is repeated multiple times. It also shows that if filters are not cleaned appropriately, a residual pressure drop appears, diminishing their performance in time.

In terms of filtration velocity or air to cloth ratio, it can be defined as the air flow going through a delimited surface of the fabric and is measured in units of (cm/sec). Mathematically it can be expressed as equation 1.4, where Q is the volumetric air flow rate (cm^3/sec) and A_c is the fabric area (cm^2).

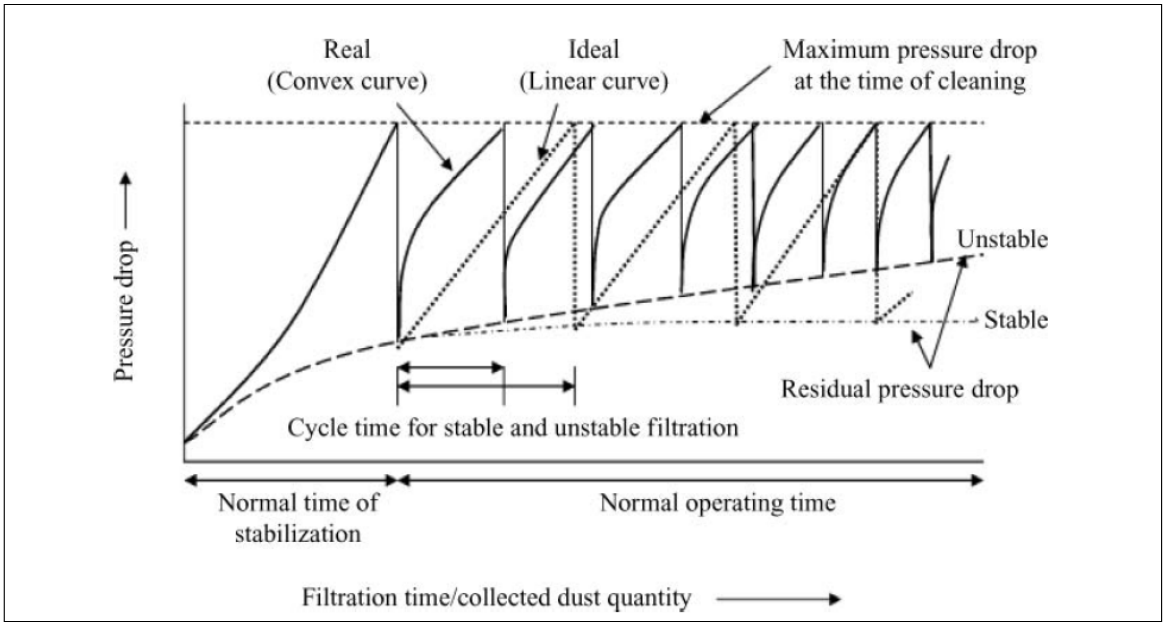

Figure 1.4. Performance curve for filters in a multiple compartment [Mukhopadhyay, 2009]

$$v_f = \frac{Q}{A_c} \tag{1.4}$$

Air to cloth ratio or A/C allows to the designer to know how many filters will be necessary to install according to a determined gas flow coming from the boiler.

1.2.5. Failures Modes

Fabric filters have three common failure mechanisms: thermal durability, chemical attack and abrasion [Beachler et al., 1995]. All filters must be chosen according to the operation temperature, among others variables. Flue gases leave the boiler at high temperatures, which filters have to withstand continuously. If temperature is too high, it is possible to cool the gases but there is a risk of moisture and acidity damaging the filter, causing chemical attack or filter blinding. The materials that currently exist in the market to manufacture fabric filters may withstand continuously from 82°C in the case of using cotton fibers, to 260°C in the case of fiberglass.

With respect to chemical attacks, filters are very sensitive to changes on flue gases composition. Therefore any change to combustion parameters (oxygen, fuel, particle loading and size distribution), may affect filter useful life, even making the fabric filter inadequate.

Cause	**Result**	**Reason**
Improper bag installation	Holes or tears in bags Reduce bag strength	Lack of proper vendor instructions Poor access to bags Improper tensioning, rough handling such as bending or stepping on bags Bags too snug for cages Sharp edges on cages
High temperatures	Loss of fabric strength Attack finish of bag causing self abrasion	Improper fabric for service No high temperature alarm Continual operation at close to fabric temperature limits
Condensation	Alters adhesion characteristics of dust resulting in mudding or blinding Chemical attack	Unit not preheated or purged properly Air in-leakage Inadequate insulation
Chemical degradation	Attack fibers and loss of strength	Improper fabric for service
High A/C ratio	Increase in bag abrasion	Change in process
High pressure drop	Increase in bag abrasion Bag tears	Poor cleaning Blind bags Increase in gas velocity
Bag abrasion	Worn or torn bags	Contact between bag and another surface High gas volumes or particle loading Large particle inspection on bag

Table 1.1. Common causes of fabric failures [Beachler et al., 1995]

Figure 1.5. Damaged fabric filters for replacement (Photo by G. Lara)

Rupture by mechanical stresses and abrasion are the most critical failure modes, because can produce pollutant leaking to the atmosphere [Beachler et al., 1995; Bush et al., 1989; Pham et al., 2012]. The most frequent cause of abrasion is related to the constant movement of the filters for cleaning purposes because they are subjected to mechanic stresses generated by the high pressure of the pulses, expanding and contracting the fabric. Abrasion generates an annual replacement rate of 25% in fabric filters [Beachler et al., 1995; Greiner, 1993]. Excessive tension also cause in some cases, abnormal movement of the bottom and stresses from the support section of the fabric, which may generates ruptures in the seam or tears of the fabric (Figure 1.5). A filter weakened by excess acidity is more likely to damage by abrasion or mechanical stress. That is why special care must be taken regarding operational parameters of the plant along the complete process, because filters are part of a system and they need to be treated as it and not as a separate component. Common causes of fabric failure are presented the in Table 1.1.

1.3. Reliability Modelling

Reliability can be defined as the probability that an item will perform its assigned mission satisfactorily for a stated time period when used according to a set of specified conditions. Its first application date back to the 1950s when US militaries started to study this concept, but it was not until the end of XX century when others industries showed real interest in their applications. During this period, maintenance costs were reaching between 60% and 75% of the equipment life cycle cost [Dhillon, 2006]. Reliability analysis uses historical information and statistical data to develop failure and maintenance studies destined to minimise non programmed or unnecessary detentions. Its development has mainly focused on industries where reliability is essential for people's safety, like aviation, trains, nuclear reactors, power generation, military equipment, computer sciences among others. The filters case is particularly interesting because their function is so important that they become as critical as an airplane turbine, although they are relatively cheap and easy to replace. When a filter fails, all flue gases that are passing through the filter are released to the atmosphere, generating dangerous emissions. Therefore, the consequences of a filter failure are not just economical, but they may also affect people's health and produce environmental damage.

To study reliability in fabric filters may be a complex problem, because there are many variables that can affect useful life of the filters. Several of this variables are very difficult to manage, like flue gases from combustion or ambient humidity, operational variables as the ratio of lime and water needed to desulphurise gases previous to filter dust particles. Therefore a filter receiving a more acid gas should have a larger probability to fail (and a less useful life) than the same filter receiving a less acid gas. If it is possible to know the most important variables and monitoring them, reliability estimation can be more precise and therefore optimal moment to inspect and/or to change the filters can be more accurate. Pulses are an operational variable, manually controlled, which depends directly on pressure drop measured. According to Beachler et al. [1995], among the variables necessary to keep monitored is pressure drop. Here lies the importance of pulses in pulse jet filters, to control pressure drop, ensuring both the proper operation and the life of the component, as this thesis will show.

This thesis is structured as follows. Section 2 contains a literature review that shows how pulse jet filters performance studies have evolved over time, and describes applications of multiple time scales methodologies to obtain a perspective of how they can be applied to pulse jet filters. Section 3 presents the methodology formulation, including mathematical and statistical basis to the study. Section 4 presents a case study application and a sensitivity analysis, including cases with different pulses frequency and different cost relations. Finally, section 5 contains the results discussion and main conclusions.

2. OBJECTIVES

2.1. Hypothesis

The development of this Thesis focuses on the hypothesis that the pulse jet fabric filters reduce their reliability in time because of the constant pulsations to which they need to be submitted to maintain themselves operatives. To be operatives means they have to reach a minimum level of capture performance, determined by system pressure drop. As will be seen in the literature review, there are several studies that mention that the useful life of the filters decreases if the pulsed frequency increases. It is explained because of fiber friction and mechanical wear which filters suffer with the high pressure air pulse that characterize this type of filter. Nevertheless, no study has been found where filter reliability is estimated considering pulses or other operational variables.

2.2. Objective

The objective is to determine the optimal replacement interval of press jet fabric filters using a reliability model with multiple time scales and looking for the minimum direct cost. In order to do this, it will be necessary to determine reliability curves for different pulsation frequency cases and to estimate cost curves for different scenarios of preventive and corrective costs.

Specific objectives

- To develop a methodology where reliability can be estimated using pulse jet filter field and extrapolated data on service hours and pulse frequency estimated from plan operators data.
- To estimate direct cost curves using the linear combination of service hours and accumulated pulses as time scale.

- To estimate optimal replacement time for pulse jet filters, according to the new time scale: service hours and pulse frequency.
- To estimate optimal pulse frequency according to the pressure drop curve of a typical filter and the cost curves previously estimated.

3. LITERATURE REVIEW

3.1. Fabric Filters

Multiple performance improvement studies have been developed since the invention of bag filters. Since the 80's when Dennis and Klemm [1980] and Dennis et al. [1981] modeled operation and pressure losses in pulse jet bag filters. Two years later Leith and Eiienbecker [1982] studied filters efficiency in particles collection. We can find a more complete study made by Carr and Smith [1984], who built two pilot plant of 10 MW each with baghouses capable of filtering up to 35000 acfm. Using two types of coal and two types of filters' cleaning methods, several studies were made trying to relate, for the first time, coal properties with filter performance. They measured collection efficiency, opacity, pressure drop and startup/shutdown cycles and SO_3 effects on filters. Even though these results are not for pulse jet, some of them, deliver general conclusions that apply for our case. It was indicated that high sulfur coal generates a dust cake more difficult to release from the filters (reverse gas and shake/deflate system), since this depends on fabric from the filters. It also says opacity increases just after a cleaning cycle, for a very short time, allowing emissions pass through the filters, which explain in part their collection efficiency. This latter result is the most important, since it relates directly the cleaning frequency of the filters with the emissions released to the atmosphere.

If we search for specific studies about coal effects on fabric filters, these date back to 1989, where Bush et al. [1989] shows the results of 24 plants which used different types of coal and cleaning methods. They defined that the most important ash properties for filter performance were particle morphology, size and cohesivity, the last one being the most important for cleaning methods, because a thicker dustcake is more difficult to release. Bustard et al. [1992] did a similar study with 25 pilot and full scale plants. They achieved the same results, but also mention that most emissions problems in a well and carefully operated fabric filters, are caused by bag failures, either holes or tears, or leaks in the ducting. Both works confirms one of the assumptions for this paper, the importance of knowing ash properties to be able to apply the right parameters to clean the filters properly.

Years later, Simon et al. [2007] took advantage of new technologies to study for the first time, pulse jet fabric filters supported by rigid rings. Using a pilot scale with 24 pulse jet filters and sensors, they measured pressure drop, dust cake deposited, acceleration, face and axial velocity of the filters during their cleaning cycle. Of our interest are their results about mechanical stresses suffered by the filters, at the top, near the air compressed nozzle, and at the bottom, where the filter ends and the air pulse leaves the filter. This stresses are greater when the filter is clogged, after several hours of operation, which gives us a hint of how the filter will debilitate in time, depending on the dust cake and the accumulated pulses, validating part of our hypothesis.

Pulse Jet filters were also computer simulated, as Dang et al. [2011] explained in their work. Using a fluid dynamic model, they achieved to emulate real results for pulse jet pressure, modifying factors as nozzle diameter, pulse jet distance and pulse jet time. From their conclusions, we rescue the importance of pulse jet pressure showed by the computer simulation, which agrees with real data, making fluid dynamic analysis an alternative to study this kind of filters.

Nowadays, Schiller and Schmid [2015] have studied how precoat materials can improve filters performance by avoiding filter clogging caused by ultrafine particles. Their results are not suitable for our case, because although they use pulse jet for cleaning the filters, they use biomass as fuel which differ from our case where pulverized carbon is use. Also, they do not mention anything about cleaning frequency effect using precoat materials.

In the next years, Suh et al. [2010] studied the parameters that affect pressure drop in pulse jet filters. Among these parameters we can find pulse pressure and pulse interval time, but they were not as important as filtration velocity, considering their effect on pressure drop. It was very useful to our work to know how pulse interval time and its interaction with pressure drop have been studied before, which corroborates its importance in pulse jet filters operations.

Despite the large amount of studies related to fabric filters, there are just a few studies that address their reliability. In the same year that Suh, Jones et al. [2010] presented a Bayesian analysis on a black carbon factory to minimize the plant's stopping time considering the failure probability of the filters. He used a delay time model to estimate the best time to inspect filters to avoid early failures, considering a minimum down time. Jone's work is very close to the analysis we are looking forward to achieve, but we will consider a specific operation parameter, as pulse frequency is, and relating it with a maintenance cost.

Another interesting work is the book written by Allan et al. [2013]. Through it, he explains the importance to study power plants reliability, considering not only the lost of revenue caused by the loss of produced energy, but the indirect cost related to the damage of customers goods, which according to them reaches 84% of total costs. Making a complete analysis, they consider the power plant as a whole, connected to a network, but they do not study in detail every element of the plant and how it affects power plant reliability, so they do not study filters as Jones et al. [2010] did and as we are going to do.

Finally, Burtraw et al. [2013] analyzed the effect of the change of environmental regulations in the reliability of different power plants and how it will be necessary to invest in elements to reduce pollution, as fabric filters, specially in coal power plants. This last work emphasises the importance of fabric filter and how the investigations regarding improving its efficiency and lowering its cost are still necessary, even in the XXI century.

The pulse jet bag filters are considered the best filtering alternative for coal operating systems from both economic and environmental perspective [Beachler et al., 1995; Mukhopadhyay, 2010; Simon et al., 2007]. These studies have been constant and have continued until the present day, taking advantage of new technologies and the more data available for filters installed in more locations.

3.2. Multiple Time Scales

Studies about components failures have shown over time that they tend to occur because of multiple variables that affect them. These failures are better explained when multiple variables are associated to the component's age generating a new and different time scale [Jiang and Jardine, 2006]. That is why, for example, a vehicle warranty is delivered by calendar time or distance covered, whichever comes first. Using a single variable and ignoring all other factors may generate estimation errors, leading to a bad decision as overestimate or underestimate a maintenance interval, causing unnecessary detentions when the equipment may be still in good conditions, or failures because maintenance was not performed on time. Choosing a right time scale is a complex decision, specially when variables affecting a component or equipment are too many, like in the mining industry Diaz et al. [2016].

Reliability with multiple time scales has been studied for several years, since Farewell and Cox [1979] first mentioned in a medicine study related to breast cancer and women's first birth, several other areas had use it to analyze factors affecting components life. Duchesne and Lawless [2000] studied in detail how to apply multiple time scales, analyzing different cases like Kordonsky and Gertsbakh [1993], who studied specific applications related to failures in planes fuselage and wing joints, considering the calendar time scale, flight hours and the takeoff/landing cycles; and also medical cases as studied by Oakes [1995] who analyzed effects of asbestos on miners. More recent examples are Pievatolo et al. [2003] who studied failures in trains door systems, considering service time and miles traveled. In mining, Diaz et al. [2016] studied the relation between multiple time scales and multiple usage profiles in haul-truck components .

This work proposes an innovative methodology from the maintenance point of view oriented to multiple time scale application to study fabric filters reliability in a coal power generation plant. In order to define the optimal replacement time to change filters, service time and accumulated pulses during operation are taken into account. The methodology considers failure probability, intervention costs, and also failure consequences in case of a plant shutdown or environmental law violations.

4. PROPOSED METHODOLOGY

Pulse jet fabric filters are consumables, which means that every time they fail, they must be replaced. Commonly, their replacement is based only on service hours, because it has been proven that the effects of coal on filters do not affect their useful life [Bustard et al., 1988]. Nonetheless, filters were traditionally chosen according to the type of coal burnt in the boiler of the plant, considering the coal chemical composition and the particle size distribution [Popovici, 2010]. The proposed methodology becomes aware of this issue and considers pulse frequency as part of the time scale for replacement along with the service hours. This is because filters pressure drop depends on particulate matter present in the flue gas and on the first variable to be adjusted for keeping filters performance which is pulse frequency. However, if pulse frequency is too high, mechanical stresses in the fabric increase, rapidly decreasing the filters' useful life.

To be able to estimate optimal filter replacement time, it is necessary to perform a reliability analysis on filters, which is a time depending function. Here is where the new time scale with service hours ans accumulated pulses is used (this latter will change if pulse frequency changes).

Multiple time scales theory, indicates that new time scale, or equivalent time, can be written as a linear combination of the chosen time scales, as shown in Equation 4.1.

$$t = t_1 + \alpha t_2 \tag{4.1}$$

In the filters case, t is the equivalent time for a filter. t_1 represents the service hours and t_2 the accumulated pulses. t_2 can be written in terms of t_1, as shown in Equation 4.2. The parameter α is used to adjust the Weibull distribution to different pulses frequencies. α can be estimated using the method of mean squared error.

$$t_2 = \theta_i t_1 \tag{4.2}$$

In Equation 4.2, θ is the rate of pulses per service hours that can be considered as a dependence on the type of coal burnt in the power plant, because a specific coal may produce more particulate matter, forcing the system to increase the filters pulsation frequency.

For the reliability analysis, the replacement times were modeled using a two-parameter Weibull probability distribution, as shown in Equation 4.3. According to this analysis, R refers to reliability and depends on time t, in this case the equivalent time. β is the shape parameter that can be calculated as the slope of the graphic shown in Figure 5.1. Similarly, η is the scale parameter representing time at which a reliability of 33% is achieved.

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}} \tag{4.3}$$

MTBI is the Mean Time Between Interventions, as shown in Equation 4.4.

$$MTBI = \int_{0}^{T_s} R(t)dt \tag{4.4}$$

Assuming that corrective and preventive maintenances may be performed to the filters at a cost C_c for corrective cost and C_p for preventive cost, respectively, the total maintenance cost C_g depends on time and is given by Equation 4.5. Usually, C_c is greater than C_p, because when a corrective maintenance is carried out it means that a failure happened and higher costs were incurred. On the other hand, preventive maintenance refers mainly to inspections and minor adjustments.

$$c_g(t) = \frac{R(t)C_p + (1 - R(t))C_c}{MTBI(t)} \tag{4.5}$$

Equation 4.5 indicates that components with high reliability are less likely to fail and need preventive maintenance. On the other hand, corrective maintenance is needed when components fail with a probability of $(1 - R(t))$. Finally, $MTBI(t)$ is used to normalize probabilities. The minimum of the global maintenance cost corresponds to the optimal replacement interval.

It is important to note that a filter failure in a power plant is critical because several pollutants are released to the atmosphere when a failure occurs, not to mention the plant shutdown to avoid legal issues due to environmental laws. For simplicity, all these costs are added to the corrective maintenance cost.

To obtain a filter optimal pulse frequency, it is necessary to reach a balance between costs and filter performance. Considering that there is not a defined theoretical formula to calculate collection efficiency [Beachler et al., 1995], pressure drop is the variable typically used to determine when to apply the cleaning pulses. If pressure drop is low, it means the filter is still collecting dust and as it is filled with it, the pressure begins to increase and the capacity of the filter to capture particles decreases as the fabric begins to clog, as seen in Figure 1.4. According to the operating parameters of the plant and the coal and ash characteristics, it is necessary to choose a pressure drop value to know when to apply a cleaning pulse. This value is often chosen based on experience. If pulse frequency increases, the filter fails to clog which implies that the pressure drop reached is lower. If this pressure drop is kept low by changing the pulse cleaning frequency, the filter is expected to improve its performance or collection efficiency.

To choose an optimal pulse frequency it is necessary to express the pressure drop as a function of the pulse frequency. As seen in Figure 4.1, pressure drop changes in time and after every pulse, it starts all over again, making a “saw” shape. When the pulse frequency is higher, the “saw teeth” become narrower and the maximum pressure drop that is reached is lower. For example, a pulse frequency of 1 pulse/hour means that every 60 seconds the filter will be cleaned and the pressure drop will fall to its minimum. In this case, at a value of 150 mmH_2O the pulse is applied. However, if the frequency is 2 pulses/hour, every 30 seconds the filter is cleaned and the maximum pressure drop at which it happens is nearly 130 mmH_2O, and so on.

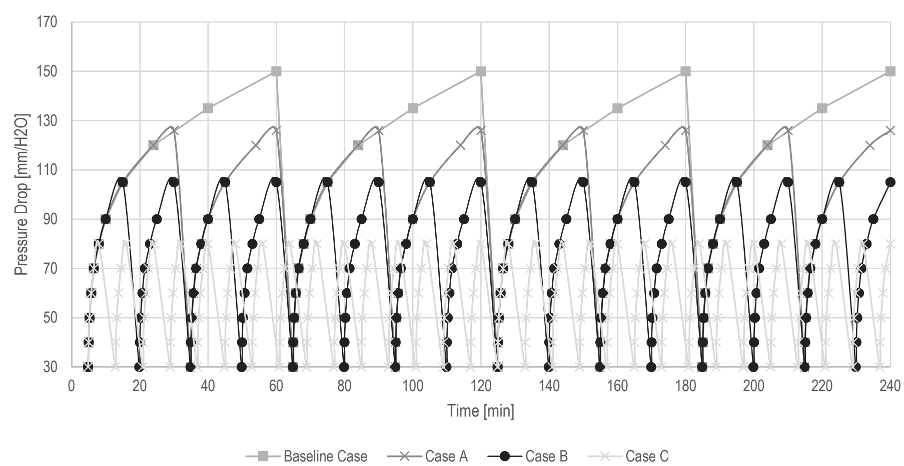

Figure 4.1. Pressure drop in time with different pulses frequencies

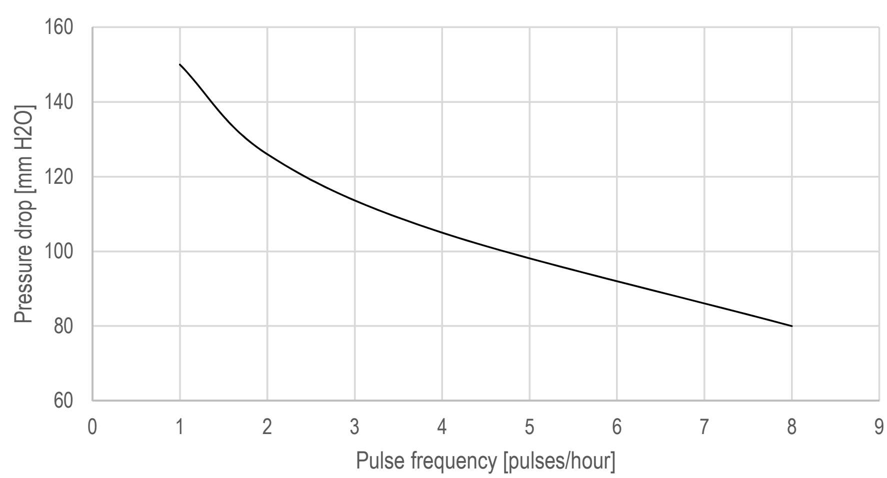

Figure 4.2. Pressure drop as a function of pulse frequency

If the maximum values from each pulse frequency case is taken into consideration, an idea of how pressure drop changes with pulse frequency can emerge. It can be see in

Figure 4.2 how pressure drop decreases as pulse frequency increases, this means that the filter is cleaner the more pulses are applied.

Taking this approach, it can be said that the higher the pulse frequency, the better since filters are always clean enough to maintained an optimal performance. However costs show that the lower the pulse frequency the better, because is less expensive. Therefore, both curves must cross, considering pulse frequency as the independent variable. The optimal value will be at the intersection of pressure drop (performance measure) and cost curve.

5. RESULTS

5.1. Case Study

Consider a power plant with two pulse jet fabric filter systems. Each system has eight sections with 252 filters. The filters are made of a homopolymer acrylic designed to work with temperatures under 100°C.

The filters' cleaning sequence is initiated when a pressure drop of 150 mm of water column is measured. If the filter reaches the pressure drop limit again before the cleaning sequence is over, it has to wait until it restarts. Otherwise, the plant's procedure activates the cleaning process every one hour.

Since filters are not inspected regularly, operators wait until the filters fail in order to replace them. When sensors show values of particulate matter in the chimney exceeding a defined limit, it means that filters have failed. In these cases, the plant is forced to stop and filters are inspected and replaced if necessary.

5.2. Results

Using the data delivered by plant operators, a record of failures was estimated based on a Weibull distribution with parameters $\beta = 1.98$ and $\eta = 10.44$ khours (one khours is equivalent to 1,000 hours) without considering pulses yet, as seen in Figure 5.1. To different pulse frequencies, β stays constant and η increases along with pulse frequency, from 11.2 khours for one pulse per hour to 15.0 khours for six pulses per hour. Then, using the method of mean squared error, an α of $0.073\frac{hours}{pulses}$ was obtained (see Equation 4.1).

The reliability function was calculated considering four cases, shown in Table 5.1. The base line case considers actual pulse frequency in the studied plant. In the proposed cases, according to Equation 4.3, θ_i represents frequencies of one, two, four and six pulses per hour. Figure 5.2 shows the reliability curves for all cases.

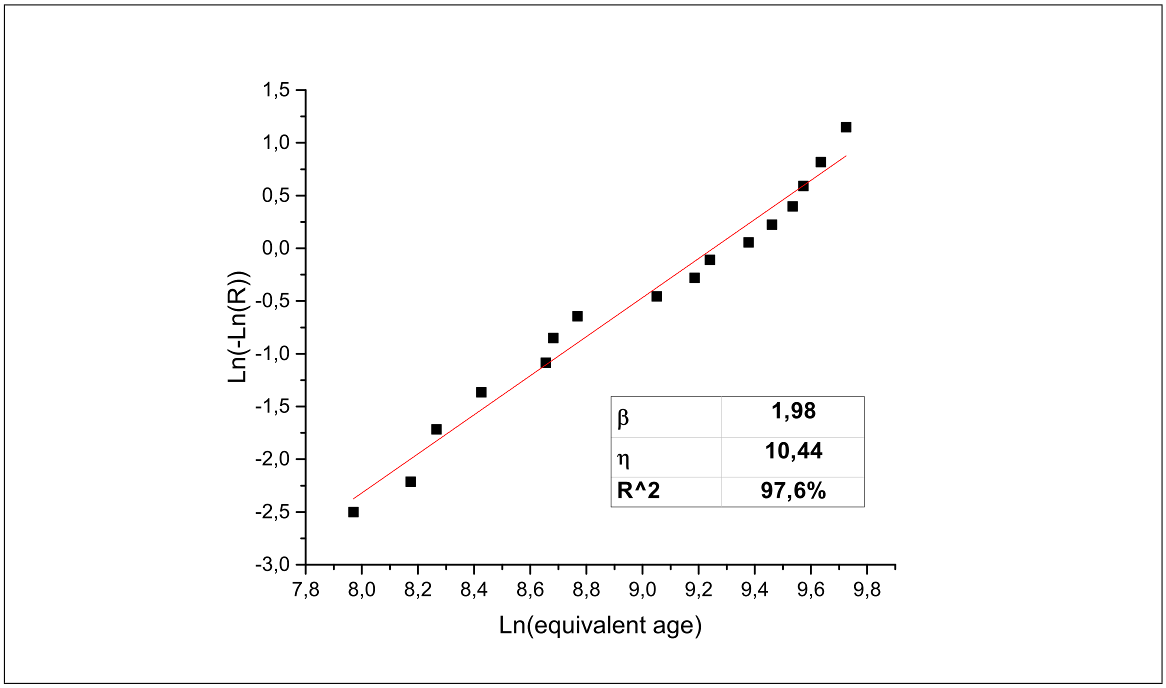

Figure 5.1. Weibull diagram

Table 5.1. Pulsation frequencies and Weibull parameters of studied cases

Case	θ_i [$\frac{pulses}{hour}$]
Baseline	1.0
Case A	2.0
Case B	4.0
Case C	6.0

For the maintenance cost analysis, a corrective cost of five times the preventive cost is considered: $C_c = 5$ and $C_p = 1$ monetary units (mu). Due to confidentiality reasons, monetary units are considered instead of a specific currency. According to Equation 4.5, the global cost reliability is calculated and shown in Figure 5.3 for all cases from Table 5.1.

For baseline case, the minimum cost is 0.39 mu/khour and is reached at 5,400 hours. On the other hand, case A and B reaches the minimum at 5,000 hours with a cost of 0.44 and at 4,600 hours and 0.49 mu/khour respectively, 13% and 26% higher than baseline case. Finally, case C reaches a minimum cost of 0.54 mu/khour at 2,800 hours.

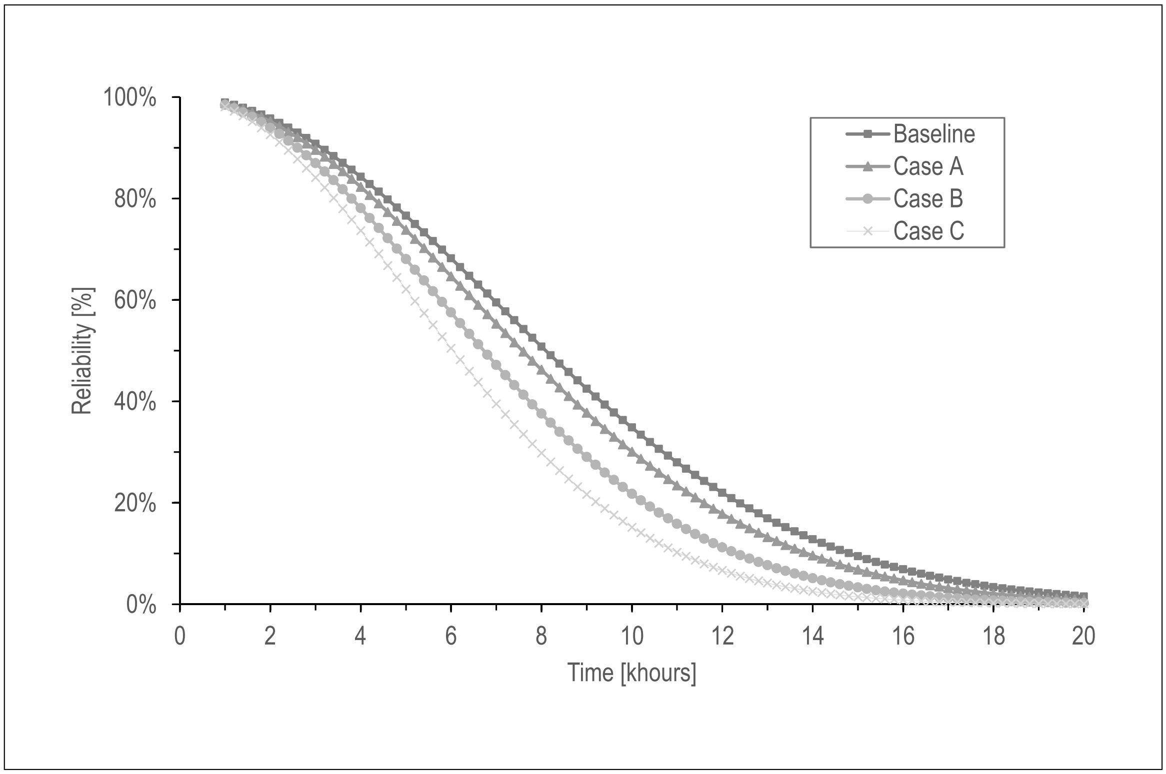

Figure 5.2. Filter reliability for all cases studied

It should be noted that including pulse frequency implies using equivalent time to calculate reliability. If pulse frequency is high, more pulses will accumulate and the filter will degrade faster. This behavior is shown in Figure 5.2, where the case with higher pulsation frequency has the worst reliability. For example, baseline case at 10 khours has a reliability of 34.8%, while case A has 30% reliability, case B has 21.8% and case C has 15.2%, all of these at the same 10 khours. This can be interpreted as accelerated damage of filters caused by excessive pulsation.

To evaluate the differences between the cases, a global maintenance cost analysis was performed. Results are presented in Figure 5.3. They show that higher frequencies require earlier replacements: by increasing the frequency from 1 to 2 pulses per hour (baseline to case A), the replacement interval decreases from 6,000 to 5,000 hours and the maintenance cost increases 13%. Similarly, increasing the frequency from 1 to 4 pulses per hour (baseline to case B), despite the replacement interval remains at 5,000 hours, the global

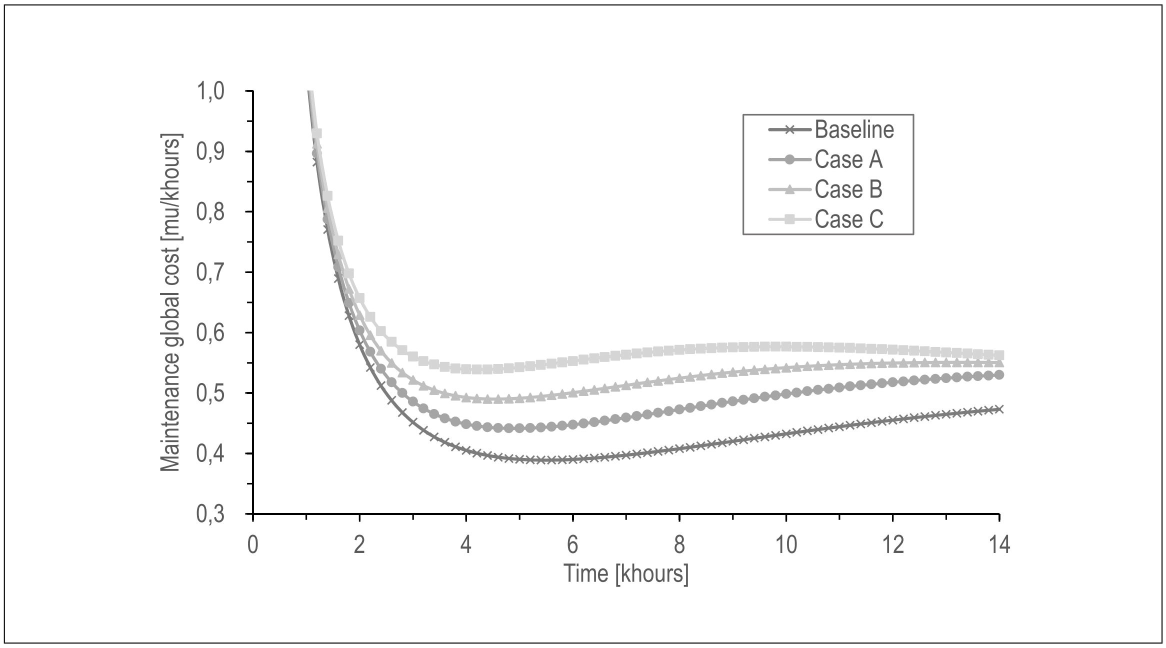

Figure 5.3. Global costs for all cases studied considering a preventive:corrective cost relation of 1:5

cost increases 26%. Finally, if pulse frequency reaches case C from baseline, a 38% cost increment can be seen.

In order to obtain optimal pulse frequency, a pressure drop estimation was performed, as seen in Figure 4.2. The data used for this estimation was based on information collected in the field. Since pressure drop is being used as an indicator of the filters performance, it is contrasted with the cost curves in Figure 5.3. This results in the final graph where these two variables can be appreciated together, both depending on the pulses, in Figure 5.4.

It can be observed that optimal pulse frequency increases when cost ratio decreases, because when corrective cost is similar to preventive cost, it is not worth performing maintenance, it would be best to take full advantage of the filters until they fail. However, when corrective costs are significantly higher than preventive, it is better to control pulse frequency. In the case of a 1:8 cost ratio, pulse frequency recommended for this pressure drop estimation is 2.4 pulses/hour which means one pulse every 25 minutes. For 1:7 cost ratio case, pulse frequency increases to 2.9 pulses/hour and for 1:6 cost ratio it increases to 3.6 pulses/hour, which means one pulse every 17 minutes approximately.

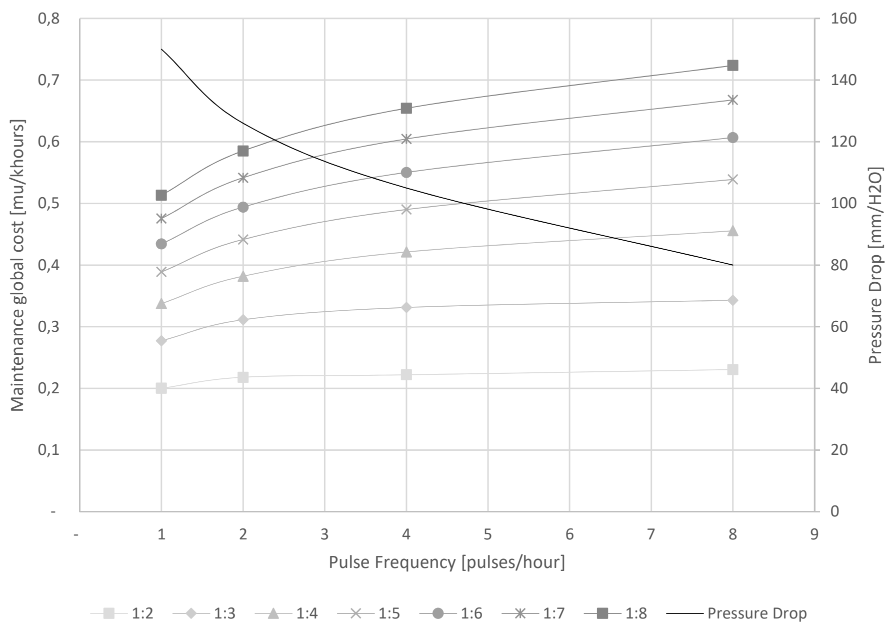

Figure 5.4. Optimal pulse frequency with different costs ratios

From an economic point of view, the energy that is not produced when a power plant is forced to shutdown becomes a loss of profit. It can be considered as the cost for the time required to detect the failures and replace the damaged filters. This cost is even higher if indirect costs are added to the analysis, like industrial and commercial damage. Considering the current scenarios of global warming and terrorist threats, more and more studies are carried out on the risks, costs and consequences of a power shutdown or blackout. For example, in LaCommare and Eto [2004] total annual cost of a blackout in the US is estimated between 22 and 135 billion dollars. They also showed that momentary interruptions (lasting five minutes or less) have more effect than sustained interruptions. For more details, ICF [2003] made an analysis of the August 14th, 2003 blackout in the US, calculating their total cost between 7 to 10 billion dollars. In Chile, according to the information in CDEC-SIC [2013], power losses in 2013 were equivalent to 1609.8 GWh, the maximum since 2004. Just in direct cost, considering the residential kWh value for 2017 of 112.36 CLP (www.eneldistribucion.cl), it means a loss of profit of 180,877 million CLP or approximately 266 million dollars annually.

6. SENSITIVITY ANALYSIS

A sensitivity analysis was performed to study how results on replacement time change if the ratio between preventive and corrective maintenance costs changes. This analysis was performed for the same four cases, considering ratios of a corrective cost from two times the preventive cost until eight times the preventive cost. The comparison is presented in Figure 6.1. Results are within expected, the worst case scenario is Case C: the highest pulse frequency and a corrective cost of eight times the preventive cost. This analysis shows that the greater the difference between preventive and corrective costs, the greater the difference between the minimum costs, which will determine the optimal replacement time.

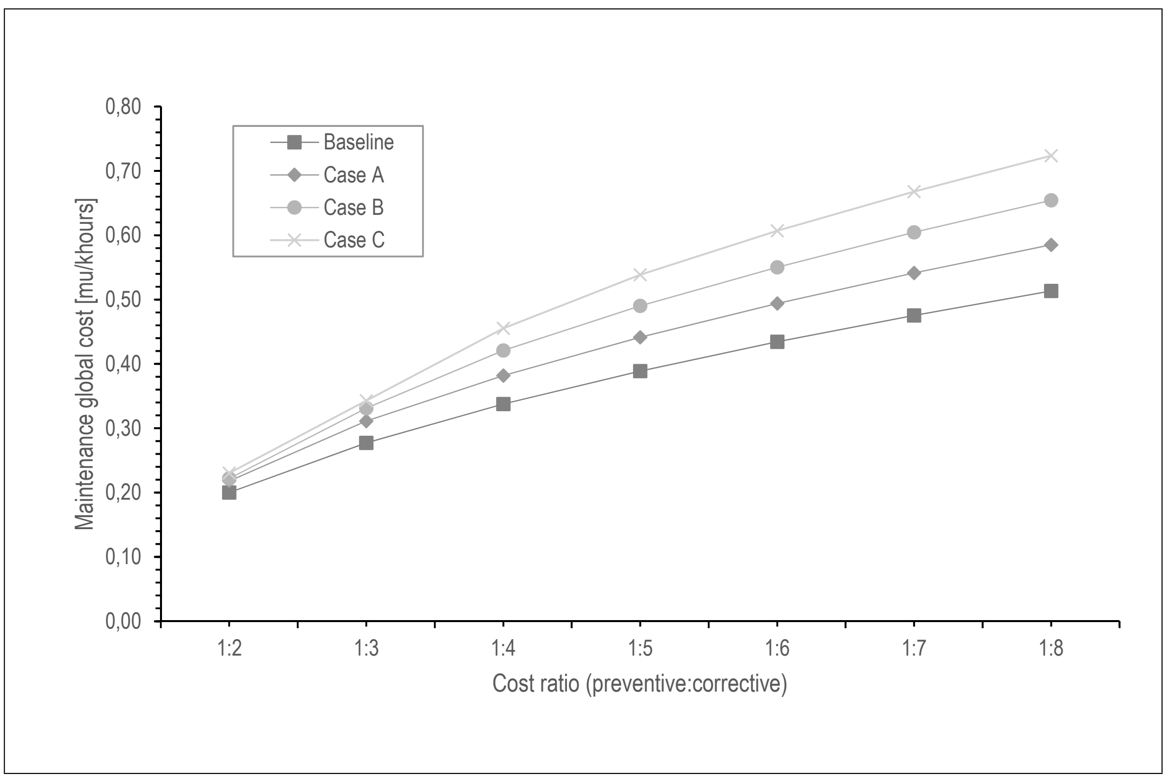

Figure 6.1. Cost sensitivity analysis

Considering the optimal replacement interval given by the global maintenance cost analysis, it is also interesting to study the relation between preventive and corrective maintenance cost with the replacement interval. As expected, if the difference between preventive and corrective cost is minimum, the maintenance cost curve is flatter, therefore, there is more flexibility to choose the replacement time without generating higher costs. On the other hand, when the cost difference between preventive and corrective cost is too high, the cost curve has a clear minimum, limiting the replacement time to avoid abrupt cost increments. An example is shown in Figure 6.2, where baseline case is modeled for different cost ratios. It can be observed how the minimum cost moves changing the optimal time replacement.

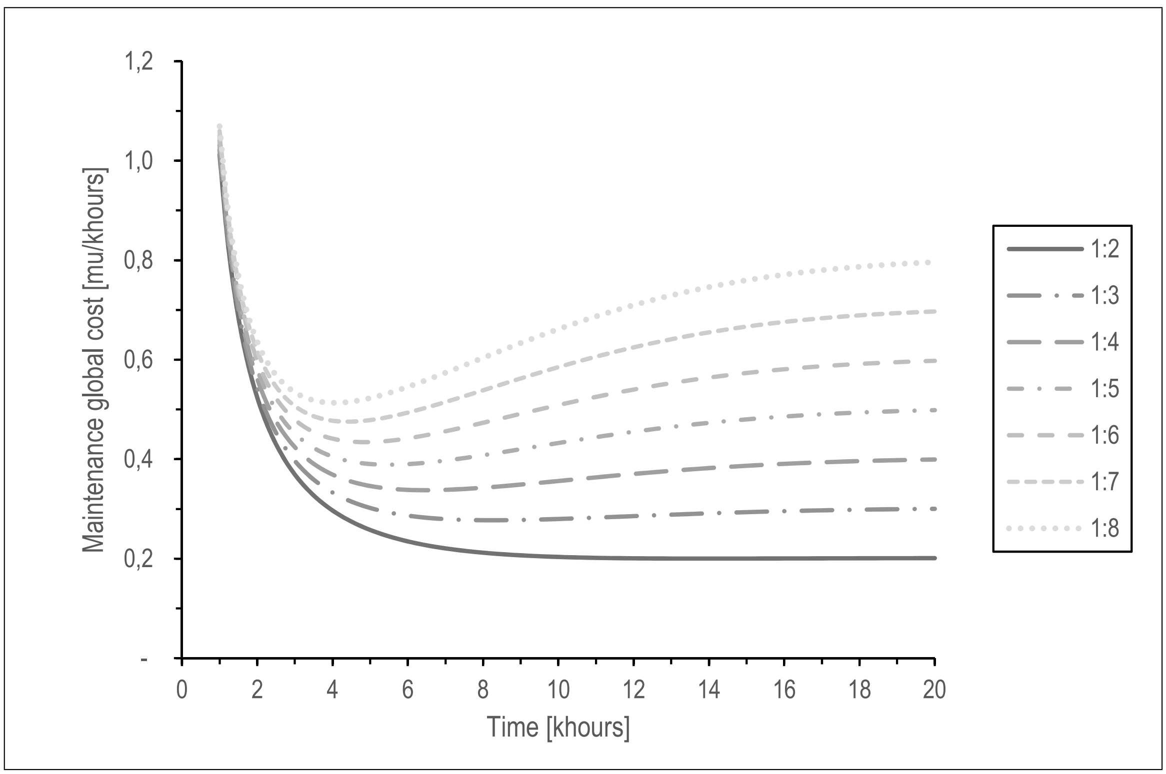

Figure 6.2. Replacement interval sensitivity analysis for different cost ratios ($C_p : C_c$)

7. CONCLUSION

This thesis shows that pulse jet fabric filters with the same service time are not necessarily in the same condition. This condition depends on the accumulated pulses that have an accelerated aging effect on filters. This effect modifies their reliability curves and, therefore, the optimal replacement interval, according to the global maintenance cost curves. The results show that a higher pulse frequency leads to higher maintenance costs because of a decrease reliability leading to an early replacement of the filters. When the difference between preventive and corrective cost is too high (6 times or more), maintenance cost increases faster, moving the replacement time earlier. This will generate more replacements and, therefore, more direct and indirect costs related to stopping the system in order to do the maintenance. The methodology used in this thesis is a supporting tool to make decisions and it has to be complemented with an analysis of filter performance, which will change according to the flue gas characteristics. If pulse frequency has to rise in order to obtain a cleaner gas, this methodology is appropriate in order to realise that maintenance costs may rise. Therefore, it is necessary to balance costs with benefits.

If the plant operates with a very high pulse frequency because of lack of awareness of filter operation (as the case study) and this frequency decreases 4 or 8 times, as from Case B or C to baseline case, maintenance costs can be reduced up to 26% for Case B to 38% for Case C, for a preventive and corrective cost ratio of 1:5. If this ratio increases to 1:8, this reduction can be up to 29% and 42% respectively. But if we take into account pressure drop analysis as a measure of filter collection efficiency, it is possible to obtain an optimal pulse frequency to clean the filters. In the case studied, a pressure drop estimation was made and contrasted with maintenance cost analysis. These results showed that when corrective costs are very high, pulse frequency is low, maintaining a pressure drop adequate to keep the filter operating adequately. For this estimation, for a cost ratio of 1:8 is recommended to maintain a pulse frequency of 2.4 pulses/hour with a pressure drop of $120mmH_2O$, a better value than the plant in this study, where they work with a value of $150mmH_2O$ and a pulse frequency of 1 pulse/hour.

Under real operational conditions, doing a filter replacement should be a process meticulously planned, knowing all variables and operational conditions. This way the replacement time chosen should be the best, for plant conditions, filter useful life and costs (maintenance, direct and indirect). If in case of an some emergency, filters must be replaced, plant operators should take note of the operational conditions under which the emergency occurred, to prevent it from happening again.

Future lines of work include (i) a more detailed analysis of the filters' function, operation and maintenance conditions considering more variables like temperature, humidity and ash composition; (ii) an extended analysis to other pulse jet filter systems and plants, like smelting plants; (iii) an economic analysis that includes the costs of each type of coal available on the market based on their quality and the effect they have on the number of pulses, and (iv) a reliability analysis that includes all plant equipment that may be affected by the type of coal used in power generation, always keeping the multiple time scale point of view.

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