Case study of pipeline failure analysis from two automated vacuum collection system.

J.A. Farré[1,2], R. Salgado-Pizarro[3], M. Martín[3], G. Zsembinszki[2], J. Gasia[2], L.F. Cabeza[2], C. Barreneche[3], A.I. Fernández[3*]

[1]Urban Refuse Development, PCITAL Gardeny, Edificio H2, planta 2ª, 25003 Lleida, Spain

[2]GREiA Research Group, Universitat de Lleida, C/ Pere Cabrera s/n, 25001 Lleida, Spain

[3]Departament de Ciència de Materials i Química Física, Universitat de Barcelona, C/ Martí i Franquès 1, 08028, Barcelona, Spain.

* Corresponding author e-mail: ana_inesfernandez@ub.edu

Abstract

Conventional municipal waste management systems based on collecting and storing waste for future management are cost-effective and flexible. These systems present significant problems such as odours, plagues and hygiene problems caused by their storage and greenhouse gas emissions from garbage trucks used for the transport of waste. The Automated Waste Collection System (AWCS) and Automated Vacuum Waste Collection (AVWC) systems, in which waste is transported directly underground to the processing plants, are efficient collection systems and respectful of the environment as alternatives to traditional systems. The pneumatic system reduces the value of the per capita generation of general waste. The present study explains the origin of pipe failure in two different AWCS factories, as well as the identification of the failure phenomena. To carry out the study, a classification of 90 failure cases by primary cause was

performed, followed by recommendations to avoid these failures in the future. Moreover, a computational fluid dynamics (CFD) simulation was performed in order to help in the failure determination and the key recommendations to avoid the most common and frequent failures.

Keywords: pipeline, waste management, pneumatic waste collection, failure analysis, Automated Waste Collection System (AWCS), waste management, Computational Fluid Dynamics (CFD)

1. Introduction

Traditional systems of municipal waste management rely on the waste collection and storage in dumpsters until their recollection and transport by a local waste management agency. Although these systems are really flexible, they have important drawbacks and environmental impacts, such as odours and plagues due to the waste accumulation in the dumpsters, hygiene problems, noise, traffic congestions and greenhouse emissions from garbage trucks used to waste transport, among others (Hedden, 1975).

Therefore, in the last years the installation of a pneumatic underground collection system, like Automated Waste Collection System (AWCS) and Automated Vacuum Waste Collection (AVWC) systems, has increased due its high collection efficiency and eco-friendly waste management. AWCS and AVWC systems are based on the garbage collection and transport via underground pneumatic pipelines to the treatment plants, hence they eliminate the environmental impact and drawbacks of the traditional systems. This is reported in comparative studies of the overall potential impact of different collection systems, like AWCS, multi-container and door-to-door, using Life Cycle Assessment (LCA) or Life Cycle Inventor. The implementation of a pneumatic waste collection system produces a local reduction of the CO_2 emissions, a less traffic congestion and a decrease of the energy demand due to the transport of the garbage via underground than by trucks (Chàfer et al., 2019; Iriarte et al., 2009; Kogler, 2007; Punkkinen et al., 2012). Moreover, in the J. H. Oh et al. study is reported that the city with an AVCS presents lower general waste generation per capita than the city with conventional garbage trucks (Oh et al., 2016).

Although these systems require significant capital costs to implement, they have improved environmental characteristics and lower operating costs than conventional systems. As it is reported in the study of Nakou et al. in where makes a financial and economic evaluation of use AVCS in Athens, Greece (Nakou et al., 2014).

Teerioja et al. make a hypothetical economic comparison between AWCS and door-to-door system in an existing and dense populated area, Helsinki, Finland (Teerioja et al., 2012). It is concluded that the door-to-door system is six times more economic that AWCS, due to the high cost to install the AWCS in an already constructed residential area and suggesting that in new residentials areas the cost will be reduced. Nevertheless, the key factor is the large investment cost and the economic value of the land.

The pneumatic collection system is not a novel idea (Zandi and Hayden, 1969). The firsts AWCS and AVWC factories appeared in the 70s, as in the commercial complex Disney World, Florida, USA (1971), the Summint Plaza, Jersey, USA (1972), Roosevelt Island, USA (1975), Barcelona Spain (1992), Leon Spain (1997) and hospitals (Bravo, 1975; Dallaire, 1974; Jackson, 2004; Kown, B. T; Kass, 1973; Laux-bachand, 2003). Nowadays, the studies of the pneumatic waste collection systems reside on factories optimization using new mobilization techniques (Esar Fern Andez A et al., 2015; Fernández et al., 2014) and in their implementation on the smart cities infrastructures (Popa et al., 2017).

Designing and constructing AWCS remains a technology challenge. To fully understand the magnitude of this challenge, one must take into account the extreme conditions that affect the various components of AWCS systems. One of the most critical components of these systems that is directly linked to the viability of the AWCS factory are the pipes. The pipes are in direct contact with the waste transported at high velocities, where the waste may have all types of geometries and dimensions, and may contain improper components of the recollected fraction, like glass and other ceramic material of high hardness; this entails the attrition of pipes. Wear due to abrasion and erosion has a severe adverse effect on pipelines, joints and elbows. (Njobuenwu and Fairweather, 2012; Zdravecká et al., 2014). At the same time, the pipes are subjected not only to possible corrosive conditions on the ground where they are installed, also to the acidity produced by the organic waste they can transport (Reyes, 2015).

In order to move forward in the construction and design of AWCS factories, and in particular in its pipes, it is necessary to know in detail the working conditions. (soil properties, type and amount of waste to be transported, temperature, etc.). It is also necessary to know the properties offered by the different materials available in the market and evaluate their long-term economic viability. Another way forward in the design of these plants is the study of current operating plants and their failures.

The failure analysis process consists of collecting and analysing the information available to determine the primary cause of failure as says ASTM Standard E 2332-04 (ASTM Standard E 2332-04, 2004) and Failure Mode and Effect Analysis (FMEA) (McDermott, 2011), thus being able to apply corrective actions and preventive measures in the design of future plants. The Ishikawa diagram, also named tree and Fishbone diagram, is a powerful tool to define the cause and effect, which provide a list of possible problems cause or required parameters to ensure the success of the effort against end pipe failure are given, for this case (Ishikawa, 1986).

Prediction of erosion attrition becomes a very useful tool in designing and selecting the equipment needed to prevent or reduce the occurrence of such failures. There are many numerical and experimental studies where erosion of pipes was investigated and studied, mainly thanks to the economic investments of the oil and gas companies. However, the mechanism that causes erosive attrition is not yet well defined (Parsi et al., 2014). In general, the numerical models used for the prediction of erosive attrition fall into three categories: empirical, mechanistic and based on Computational Fluid Dynamics (CFD) simulation. As mentioned above, the erosion mechanism is complicated and most models for predicting erosive attrition are a combination of the three categories. It is important to note that in many cases, erosive attrition cannot be avoided, but it can be controlled to keep it within limits that are acceptable to the end user ("DNV GL. DNVGL-RP-O501: Managing sand production and erosion.," 2007).

Since the end of the 20th century, CFD has played an important role in the analysis of erosion caused by solid particles, since it reduces the economic cost associated with laboratory or field experiments. Additionally, CFD models allow understanding the complexity of the fluid dynamics associated with the process and the change in design and operating conditions. On the other hand, the complexity of the erosion phenomenon, as well as the number of variables involved, make obtaining a 100% reliable CFD model a challenging task.

The study of erosion using CFD models consists of three main steps: flow modelling, particle tracking, and erosion calculation (Figure S1). Regarding flow modelling, in the present study, a RANS (Reynolds-averaged Navier-Stokes) treatment was used in the Euler reference framework with a stationary model of turbulence of the k-ω family. This model of turbulence was selected to efficiently determine the turbulence of the flow both in the regions near the wall and in the regions far from it. Particle tracking was modelled as a discrete phase whose particles are dragged into a Lagrangian frame of reference by solving ordinary differential equations with Newton law of motion in a transient state. A one-way coupling between flow modelling and particle tracking was considered, assuming that flow affects particle behaviour, but not vice versa, to decrease the computational cost of the model. Therefore, the behaviour of the fluid was first calculated using a stationary study, and then the trajectories of the particles were calculated using a transient study.

Regarding erosion calculation, different models are available in the literature, which were developed to calculate by means of simulation the erosion caused by the impact of erosive particles. The vast majority of existing models consider sand as an erosive agent and under special boundary conditions. However, the same models can be adapted so that they can be used for other erosive agents by modifying their corresponding properties. It is important to mention that erosion is a complicated phenomenon that is affected by different parameters and that currently there is no model able to accurately predict erosion under different boundary conditions.

Four main models were found in the literature that could be used to describe and analyse the erosion process on different surfaces, such as the one developed by Finnie (1972)(Finnie, 1972), Oka and Yoshida (2005) (Oka et al., 2005; Oka and Yoshida, 2005), Ahlert (1994) (Ahlert, 1994) and the one included in Det Norske Veritas (2007) (Det Norske Veritas, 2007).

The main objective of the present study is to explain the origin of pipe failure in two different factories of AWCS, as the identification of the failure phenomena and to carry out the study classification of 90 failure cases by primary cause. Moreover, the ultimate goal of this paper is to help prevent common issues related to erosive attrition by performing simulations based on CFD, followed by recommendations to avoid the most common and frequent failures in the future.

2. Methodology

The composition of the waste proceed in the plants under study is diverse. However, notice that the waste is basically composed by all the residues produced in this area: general waste, envelopes, packaging and containers, and paper and cardboard.

The waste makes a variable path depending on the point of discharge at which it is introduced into the system. Therefore, the distance is from 150 m to 2,000 m, passing through the different elbows and junctions that define the route.

The waste is different depending on the time of year, the place, etc. For these 2 plants, their location is in Spain, but there are differences in the composition of each of the fractions. For example, a historic center, despite collecting the same fractions, has a completely different composition to that of a newly developed area. This does not affect the pneumatic collection, as its operation is completely automatic. Once the fractions have been predefined, the system self-regulates in order to provide sufficient suction capacity for transport. In the event that one is denser than the other, the system will regulate itself.

2.1. Failure analysis

The determination of failure causes was performed by a failure analysis method in concordance with the ASTM E2332-04 (ASTM Standard E 2332-04, 2004). The process includes the collection and analysis of data about the failed component and the surrounding environment of the component/system.

The data were extracted from the pipe failure reports from two AWCS factories (Factory A and Factory B), focusing the study in the failure analysis, extracting information in order to extrapolate to other AWCS factories.

The procedure used to analyse and classify the 90 pipe failure cases was based on ASTM E2332-04. The process was divided into four steps. First, organization and analysis of the data collected of the failed component was performed. The technical information studied were operating conditions of the pipe, the employed materials, pipe installation and life record, and factory design, among others. This information is needed to determine the surrounding of the failure. Second, identification of the physical-chemical phenomena involved in the pipe failure by studying the information previously collected. Third, determination of the different causes that could produce or aggravate the physical-chemical phenomena previously identified. Moreover, an Ishikawa diagram (Ishikawa, 1986) was carried out to match the causes with different parameters, like materials, operation procedure, pipe system assembly and design. Fourth, cause analysis is performed in general terms for the two factories and specifically for each one.

2.2. Case studies

The pipe characteristics, the type of the waste transported, the welding characteristics and the failure prevention methods used in each factory are summarized (Table S1).

The pipes from the two AWCS factories were designed according to the expected amount of waste transported. The design was different for each part of the pipe system (straight stretch, elbow or connections). In addition, the pipe material used, and its characteristics were different in each factory. The welding materials used in both factories were EC-4541 and 66*66 and the method used was Metal Active Gas (MAG).

The operational conditions in both factories were the same, where the rate of waste transported was 8 – 10 m/s and the air transported was 25 – 28 m/s. Besides, the waste transported in each factory was different, paper, plastics and general waste in the Factory A and organic fraction and general waste in Factory B.

Cathodic protection was used in both factories as a failure prevention method and the Factory A, an attrition-resistant material was used in the critical zones (detected zones with a high risk of failures) as elbows and connections.

2.3. Failure phenomenon and causes classification

2.3.1. Failure phenomena

Two main physicochemical phenomena involved in the pipe failure were identified: corrosion and attrition, together with a synergic phenomenon between them known as tribocorrosion.

Corrosion

The corrosive causes previously determined were divided into two groups, according to the origin of the corrosion process, inside or outside of the pipe.

Regarding the cases located inside pipes, the corrosion could be attributed to acid pH due to the presence of organic matter and its accumulation in cavities. The leached pH during the acidification phase of the organic matter drops up to 5 and could be stabilized between 6 and 7.5 at the end of the process (Reyes, 2015).

On the other hand, the corrosion cases detected outside the pipes, some land characteristics, such as chemical composition, particle size, aeration level, electric resistivity, humidity and pH must be considered. Moreover, environment agents' actions could produce changes in land characteristics. Another important factor is the stagnate bags formation with a concentration of chloride ions (Cl^-). This Cl^- could produce localized corrosion known as pitting. EN 14301 (304) and EN 14306 (304 L) stainless steel are susceptible to this kind of corrosion.

Attrition

Two principles' typologies of attrition were identified: abrasive and impact attrition. These two typologies are complicated to differentiate because both can happen at the same time. In the two studied cases, the attrition grade is related to properties, shape, size and rate of the particles transported and the geometry of the pipe. Nerveless, a general tendency of the attrition by particle velocity, is established (Brunett, 1996), see Equation 1.

$$A = k \cdot v^n \quad (1)$$

where *A* is the erosion rate (m^3/kg), attrition, *v* is the particle impact velocity (m/s), and *k* and *n* are constants that depend on the physical characteristics of the materials involved, for most materials *n* have a value between 2.2 and 2.8 . The pipes are dealing with glass and ceramic particles that can produce attrition due to its high hardness, 489 – 550 HB.

The abrasive attrition happens when a high hardener material at a certain velocity is in contact with a lower hardness material. This contact will produce micro-cuts in the surfaces of this second material. In the studied cases, this phenomenon happens and is aggravated in the elbows and the lowest part of the pipe. Since this phenomenon relates to the pipe materials is needed to consider the different materials employed.

The pipes of stainless INOX AISI 304 and St. 37.2 with hardness (Hardness Brinell, HB) between 175 – 200 HB and 100 – 140 HB respectively, and the glass hardness is between 480 – 550 HB. Since the hardness values are very different, this could produce a high grade of abrasive attrition or rapid abrasive attrition, when the relation between hardness is lower than 1.2 (Hglass/Hpipe> 1.2), (Batchelor et al., 2011).

Considering that the critical zones in pipes are coated with attrition-resistant treatments, these hardness values are higher than the glass hardness, so no abrasive attrition should happen. The coatings applied are CDP 4666 DP/DXW and EnDOtec DO*361 with hardness between 628-685 HB and 666 HB, respectively.

The welding zones are the most critical, and it is important to select the correct material to perform the welding. Different electrodes and welding materials were used at the two factories studied. The 66*66 and EC-4541 were used with a hardness of 210 HB, 95 HB and 628 HB. Hence, the 66*66, AISI INOX 309 were sub sessile to suffer abrasive attrition or rapid abrasive attrition, but the EC-4541 due to its high hardness no abrasive attrition should happen.

The impact attrition happens in high angle elbows, protrusion pipe, pipefittings and in reparation zones where the shapes are not perfectly reconstructed.

2.3.2. Causes classification

Seven potentials causes were detected that aggravate and cause the attrition phenomena combined with abrasive and impact like glass content, waste velocity etc. In the case of the corrosion three causes were identified, and one of the tribocorrosion phenomena (Table S2). However, is important to note that there are inherent limitations in the cause classifications, which must be considered while carrying out this study. Some potential causes such as mean waste density, surface texture of waste, shape of waste particles and metal content were not included in this study, due to the wide diversity of waste shape and texture.

The corrosion and attrition phenomena could happen by different causes with very similar effects. To differentiate these cases and know the cause-phenomena-effect interrelation, an Ishikawa diagram was built, and it is shown in **¡Error! No se encuentra el origen de la referencia.**.

In the Ishikawa diagram, four principals' parameters were considered: material, operation, assembly and design. The materials could produce abrasive attrition due to glass and ceramic waste content, electrochemical corrosion by the organic fraction acidity and localized corrosion by the stagnating bag formation rich in chloride ions. Moreover, the installation operation could produce abrasion and impact attrition owing to the high rate of the waste transported especially in the change of direction zones (elbows). For the installation assembly, the welding defects can produce tribocorrosion and the pipe protrusion and pipefitting can produce impact. The installation design could produce abrasive and impact attrition because of change of direction and abrasive attrition to lack of attrition-resistant materials.

2.4. Numerical modelling

In this study, the erosion ratio caused by the impact of particles on the sample surface was predicted using the Oka erosion model (Finnie, 1972; Oka and Yoshida, 2005), assuming the values and materials properties provided in supplementary tables (Tables S3 and S4) for the different model parameters. The reason for using Oka erosion model is the higher number of model variables that are taken into account, which allow more flexibility and accuracy of the numerical analysis.

The simulations were performed using COMSOL Multiphysics 5.3 finite element software on a computer with an AMD FX™ Six-Core Processor (3.30 GHz) with 8 GB of installed RAM. For the simulations carried out for the present study, it was considered that the energy equation in the Navier-Stokes equations was not solved and the surface of the pipe was not considered as such, since the software used to carry out the simulations considers the wall as the last layer of the fluid. Therefore, no pipe thickness was specified. Also, it was assumed that the fluid was incompressible, had a constant temperature of 20 ºC and the fluid velocity was 25 m/s, while that of the particles is adjusted according to the fluid velocity profiles. In the walls of the different components, the non-slip condition was established from the point of view of the fluid and the rebound condition from the particles.

Under the impossibility to simulate real-size waste particles, which may be as big as tens of centimetres, much smaller particles (below 1 cm) with physical properties that could emulate the behaviour of soft and hard material available in the waste were considered in the simulations. Therefore, a comparative study of the erosion produced by particles with different properties (for instance different hardness values) was performed, considering materials with very different hardness values such as glass and plastic.

The glass particles were assumed as rectangular prisms with dimensions 5 mm × 7 mm × 3 mm, with a mass of 0.26 gr, and with a moment of inertia of 1.76×10^{-9} kg·m^2, while plastic particles were assumed as spheres of 5.85 mm diameter. Particles were tracked for 0.4 s for computational efficiency issues. Also, it was assumed at any pipe inlet, the particles are located at the lower part of the pipe cross-section and occupy a surface corresponding to 25% of the pipe cross-section, with a production rate of 0.01 kg/s. The component walls were assumed completely smooth with no welding at the joints between components.

Three geometries were considered for the different simulations, which are the most relevant components of the system considered in the case studies: elbows of different angles (15º, 30º, 45º, 60º, and 90º), a 30º connection, and a straight stretch with a change in the direction of 5º with respect to the horizontal plane. All these elements were assumed to be preceded, and followed by a straight pipe section to study the erosive effects of fluid and particles in the sections before and after them. A schematic of the geometries that were studied, as well as the relevant geometric parameters are provided in supplementary Figure S2.

Physically controlled mesh with an extra fine cell size was used for simulations of the 90º elbow, the connection, and the straight stretch. For the rest of elbow angles (15º, 30º, 45º, and 60º), a coarse mesh was used, since in those cases a more qualitative study on erosion was intended.

3. Results and discussion

3.1. Failure analysis

The 90 cases studied were classified by failure cause, see Figure 2. The 93% of the failures analysed are due to attrition phenomenon where the predominant cause is the attrition in elbows. This excessive attrition located in these zones is due to the glass content, waste rate and in small angles in the elbows, due to the impact of high hardness waste to the pipe walls. On the other hand, the corrosion and tribocorrosion correspond to less than 10% of the cases studied. The failures due to the assembly or design could be easily avoided in future AVC factories taking the corresponding measures as well as the faulty welding, pipe protrusion and pipefitting.

The failure cases were also classified by the components, to know the weakest parts of the factories. The 85% of the failure cases are concentrated in three components: elbows (37%), straight stretches (33%) and connections (15%). The main failure cause in straight stretches is pipefitting, while in elbows and connections the only failure cause is the high attrition (Figure S3). Additionally, the major part of the failures cases in pipe joins are due to defective welding and, as expected, the localized corrosion and pipe protrusion are located in straight stretches, because of their high probability to suffer these causes due to their high extension compared to other components.

As mentioned before, the major failed component is the elbow. For this reason, a deeper study was needed to know the most affected typology of the elbow. Elbows with a 30º angle are the most affected ones, followed by the 90º elbow and the connections (Figure S4).

Figure 3 presents the percentage of failure cause for all the failure cases studied in Factory A and B. Only 29 of the analysed cases were produced in factory A. The 29 failures occurred during 10 years. During the three first years there were any failure, and after that there were between 6-7 failure per year maximum. In factory B were analysed 61 cases. The 96% and 92 % of the cases were due to attrition that collect failures by pipe protrusion, pipefitting, lack of attrition-resistant material and abrasive attrition, respectively. In factory A the most common causes of attrition were pipefitting (48%) and change of direction (41%). The lack of attrition-resistant materials corresponds to 7% of the cases and only 4% of cases correspond to localized corrosion due to non-correct welding. In factory B the attrition cases are mainly due to direction changes (66%) and due to assembly errors (33%), like pipefitting and pipe protrusion. 5% of cases failed were caused by tribocorrosion in faulty welding, and only 3% of failures are due to localized corrosion.

B

3.2. Numerical simulations

Figure 4 shows the results of the simulations performed for the 90º elbow assuming particles made of glass. There are two main zones significantly affected by erosion: zone A and zone B. Zone A comprises the part of the elbow between angles from 25º to 55º. Zone B comprises the part of the elbow starting from 75º to 90º, the upper part of the first 150 cm of the straight pipe section after the elbow, and the lower part of the same straight section after the first 150 cm. It is evident that the most affected area is zone A, with erosion rate values up to 18 times higher than in zone B. Within zone A itself, the most affected area is the upper half, with values 1.5 to 18 times higher than the bottom half. The explanation is that in the initial part of the elbow (0º - 25º) the erosion takes place by friction since particles move mainly parallel to the surface. As the curvature of the elbow increases, the particles no longer produce erosion by friction, but also by direct impact (collision). Around 45º, there is a limit for a direct collision of particles with the pipe surface, after which particles interact with the elbow surface due to secondary collisions and friction.

Figure 5 shows the erosion rate distribution according to the results of the simulations performed for the 30º connection, in the case when glass particles enter from the lateral branch and air flows through the main pipe. In this case, the region where particles coming from the secondary branch collide with the surface of the main pipe is where erosion has a greater impact. The most affected area is comprised between 62% and 82% of the total length of the element (L1 in Figure S2), covering almost the entire lower half of the surface of the main pipe. In the case in which the erosive particles enter from the straight section of the 30º connection (not shown here), practically no erosion was observed due to the fact that there are no critical points where particles collide with the pipe surface.

Figure 6 shows the erosion rate distribution according to the results of the simulations performed for the straight stretch with a change in the direction of 5º for glass particles. The change of direction of particle movement mostly affect the lower part of the pipe area where the change takes place, as well as the lower part of the straight pipe section that follows. Specifically, the most affected area is at the junction between the two straight pipe sections, and in the first 30% of the total length of the straight pipe section that follows. However, it is important to highlight that the effect caused by the change in the direction is substantially less than in the previous component, showing the influence of geometry on the rate of erosion.

To study the erosive effect of the type of waste that flows inside the pipes, a simulation was performed for the 90º elbow considering that particles were made of plastic and was compared with the erosion rate obtained using glass (Figure S5). The erosion rate produced by glass particles is much higher than the one produced by plastic particles, highlighting the need to avoid the presence of glass in the waste collection system to prevent damages in the pipes due to erosion.

The effect of using a different pipe material of higher hardness value was also investigated. The results of the simulation performed for the 90º elbow made of a material with a hardness value three times higher than the base-case material (St. 37.2 steel) is shown in Figure 7. The comparison with the base case indicates that increasing the pipe material hardness by a factor of 3, the maximum erosion peaks are reduced by almost 50%.

Lastly, the effect of a change in the radius of curvature of a 90º elbow on the erosion rate was also investigated with a simulation for a radius of curvature that is double than the base case, for the same pipe diameter. The erosion rate decreases as the radius of curvature increases, because for higher values of the radius of curvature, the direct impact of solid particles on the pipe surface is reduced (Figure S6). However, a higher radius of curvature also implies an increase in the total pipe length, and therefore an increase in the final economic cost. Therefore, a compromise should be reached between the reduction of erosion rate and the increase of costs produced by an increase of the radius of curvature.

4. Conclusions

The major part (93%) of failure registered was originated due to the abrasive at attrition, mainly in elbows and connections (58%) and in pipefitting (31%). This phenomenon happens due to different factors, but there are two factors that are present in all the situations, these are the high glass content in the waste and the high transportation rate 8-10 m/s. If this content is reduced, the failures in the system will be drastically decreased. The presence of glass in the waste is the main cause of attrition, due to its high hardness. To reduce this effect, the glass content in the waste should be reduced, and the materials used in the pipes should have with higher hardness ($1<H_{glass}/H_{metal}<1,2$) than the hardness of the pipes used in these two factories. This fact is corroborated with the numerical simulation reflects: non-erosion was detected in the case of a 90º elbow with a 0% of glass content in the waste transported.

The results reveals that the waste transported rate is a critical parameter in terms of attrition since this parameter is directly related to the attrition grade. The higher the rate of waste transported, the higher the attrition in an exponential way. Therefore, to reduce by 20 – 25% the attrition grade involves a 10% reduction of the transport rate. So, the optimization of this rate will be convenient for each part of the pipe system, or almost in the critical zones, like elbows and connections.

At the light of the results here presented, the optimization of the base material used in the pneumatic system as well as the reinforcement with of attrition resistant materials in elbows and connections are the main recommendations to be considered for building new AWCS.

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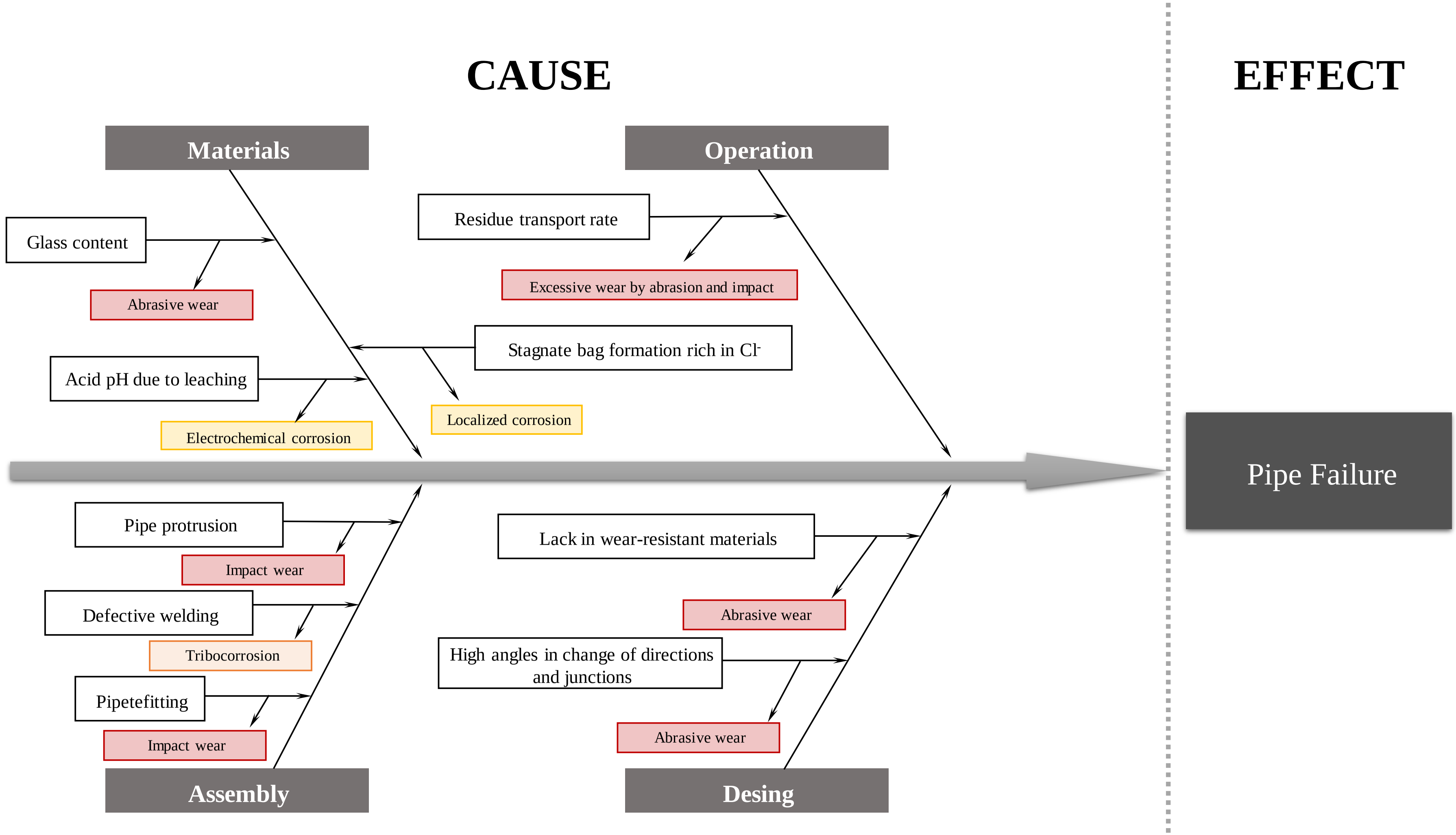

Figure 1. Ishikawa diagram of potential causes and effects of pipes in AVWCS systems

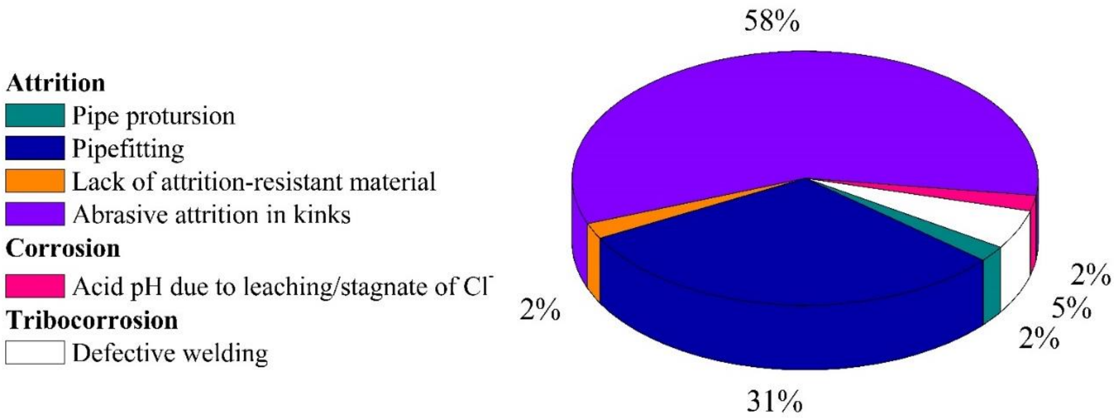

Figure 2. Classification of the 90 cases studied in both factories

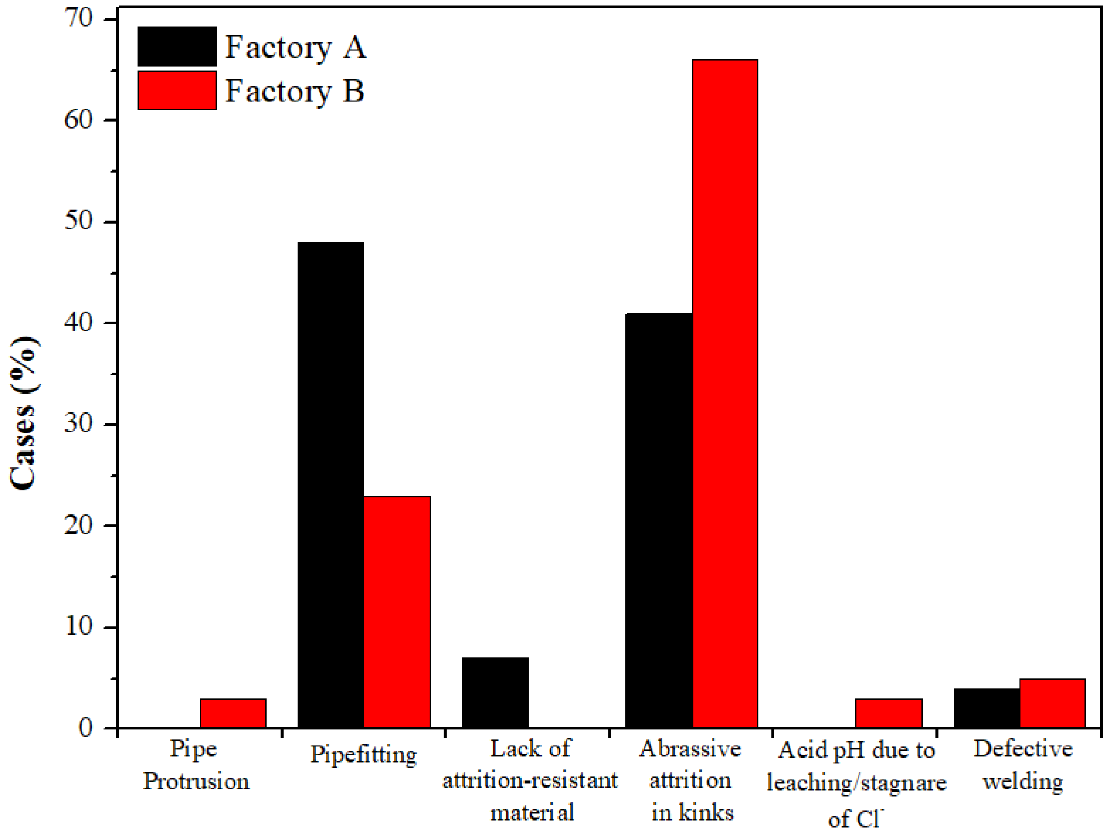

Figure 3. Classification of the 29 cases in the Factory A and 61 cases in Factory

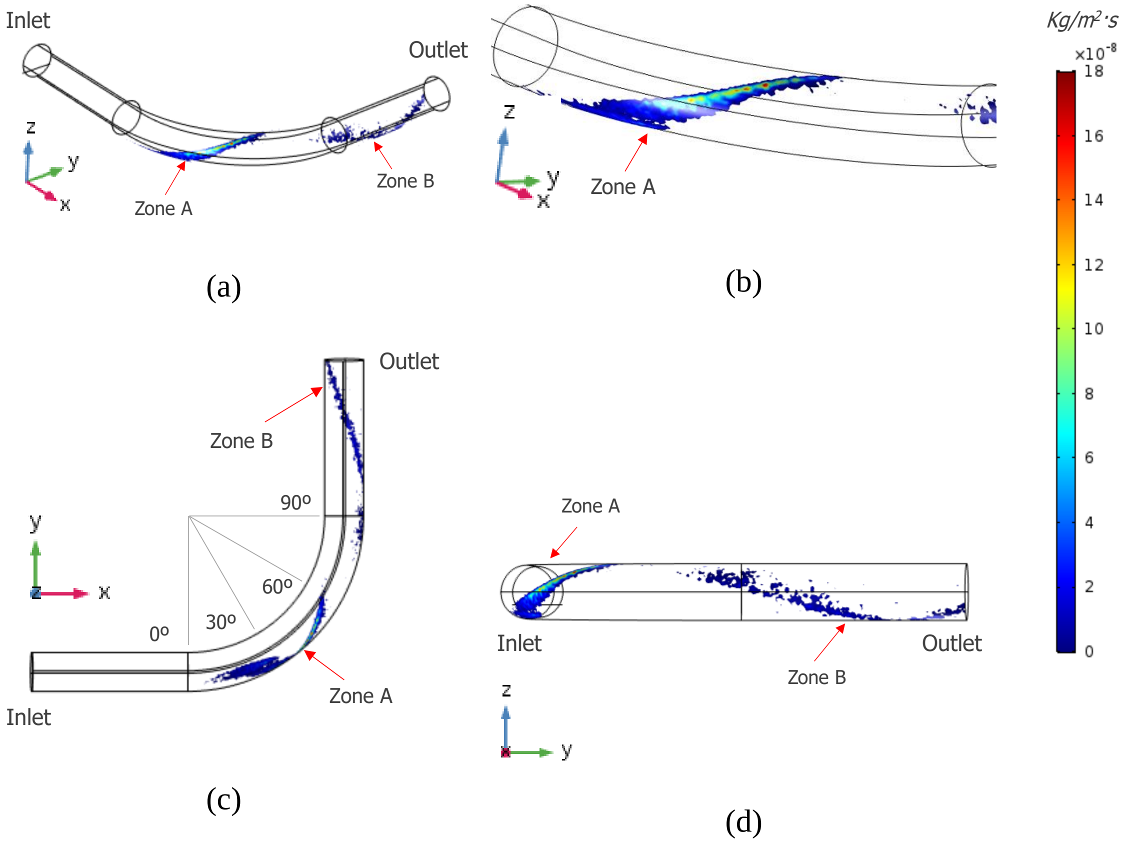

Figure 4. Erosion rate on the 90º elbow surface and on the preceding and subsequent straight sections. (a) Three-dimensional view; (b) amplified three-dimensional view of the area most affected by erosion; (c) top view; and (d) side view. Note: all values less than $1 \cdot 10^{-8}$ kg/(m·s) have been removed for better visualization.

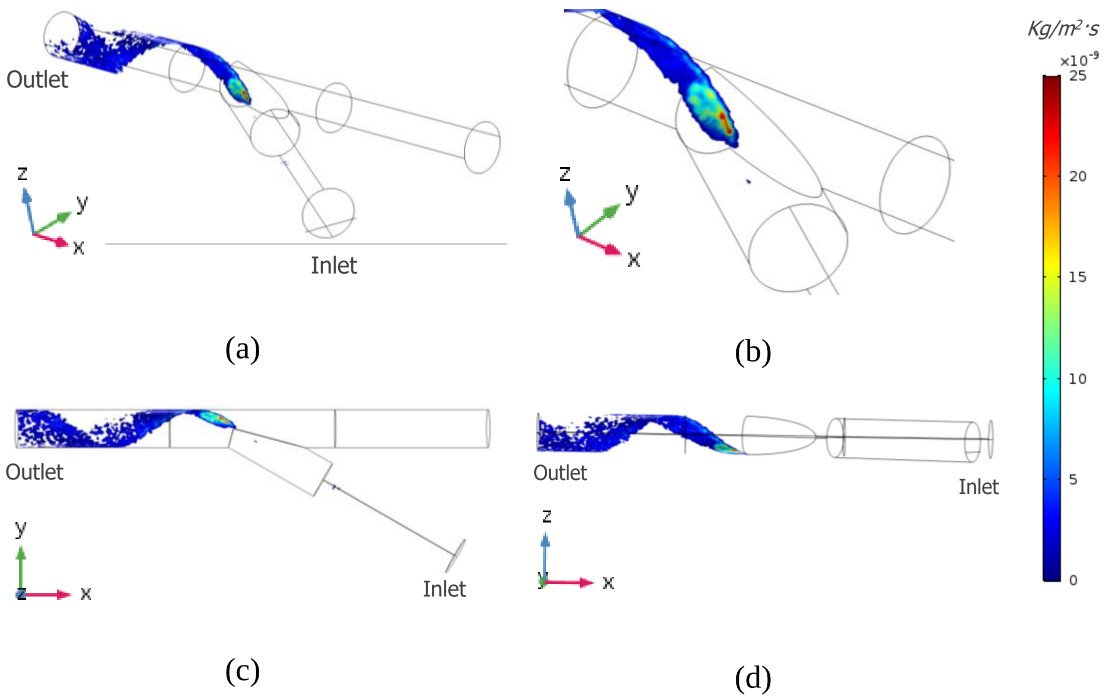

Figure 5. Erosion rate on the surface of the 30º connection and on the preceding and subsequent straight sections for particles entering from the lateral branch. (a) Three-dimensional view; (b) enlarged three-dimensional view of the area most affected by erosion; (c) top view; and (d) side view. Note: the measurement scale is different from that of the 90º elbow for better visualization.

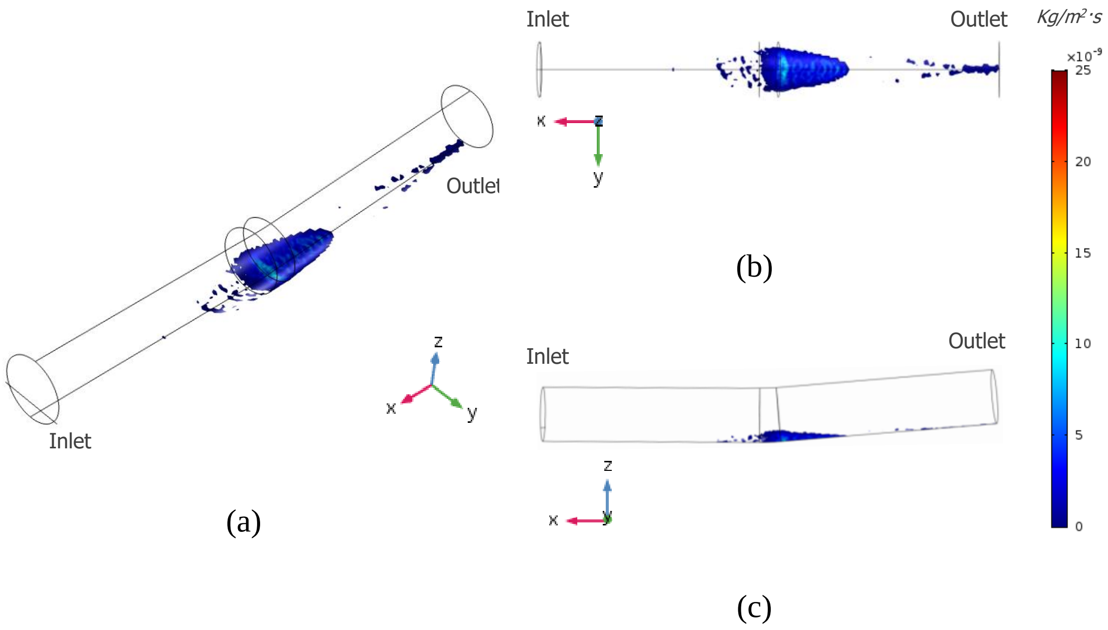

Figure 6. Erosion rate on the surface of the preceding and subsequent straight sections of a 5º change in direction. (a) Three-dimensional view; (b) top view; and (c) side view.

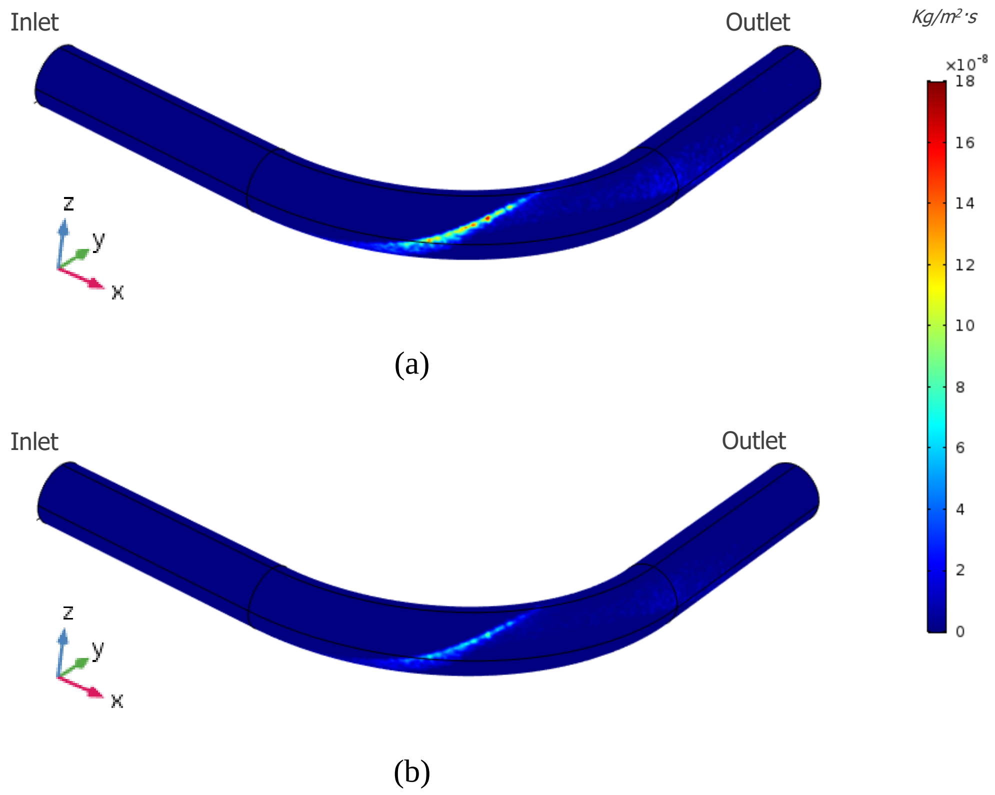

Figure 7. Erosion rate on the 90º elbow surface and on the preceding and subsequent straight sections for a pipe made of (a) steel St. 37.2 and (b) a material with a hardness three times higher than steel St. 37.2.