Life Cycle assessment of a sterile water generator circuit for bottling plants

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Abstract: Life Cycle Assessment (LCA) of two different equipment for maintaining the sterility of homogenizer pistons has been performed. The aim of this research was to compare a traditional machine (pressurized steam barriers system) with an innovative sterile water generation technology, by considering the whole life cycle. Primary data related to the two analysed products have been gathered from a homogenizer manufacturer of the Parma province, while Ecoinvent database v3.1 has been used as source of secondary data. The assessment has been performed using International Life Cycle Data (ILCD) impact assessment method. The results of the analysis show that the new technology has a lower environmental impact than the traditional one in all the considered impact categories. This is essentially due to the lower steam consumption required by the new technology during the use phase. Another outcome of the study is that the use phase is the main cause of environmental burdens, responsible on average by more than 80% of the total impacts except in 3 categories only for the NiSoPURE (Human toxicity; cancer effects ; Freshwater ecotoxicity; Mineral, fossil & ren resource depletion).

Keywords: LCA; Environmental impact; Steam water generator; bottling plants.

1. Introduction

Vermeulen et al. (2012) estimated that food production is responsible for up to 29% of the anthropogenic greenhouse gases emissions; this is obviously due to several phases along the food supply chain such as crop, industrial transformation and packaging, distribution and finally food losses and wastage. As far as dairy products are concerned, it has been estimated they are responsible for 8 to 10% of environmental impacts of European consumption (Weidema et al. 2009).

Studies based on the methodology of life-cycle assessment (LCA) clearly show that currently one of the main challenges in minimizing the environmental impact of food processing is that related to cleaning and disinfection (sanitation) of equipment and facilities. This is in fact one of the most intensive operations in consumption of water and energy (linked to the generation of CO2 emissions and waste water) and the use of chemicals (chlorine, detergents, disinfectants).

The cleaning and disinfection of equipment and facilities in the food industry is mandatory to maintain an adequate level of hygiene and food safety of processed foods, but it has a high environmental impact (consumption of water, energy, cleaning products, water residual and CO2 emissions).

On the other hand, the sanitation of equipment and facilities in the food processing industry is crucial for food security and the quality of the final product, and therefore a sine qua non requirement for the industry. As such, the frequency and intensity of cleaning and disinfection actions will depend on the hygiene requirements, the efficiency of the cleaning process and the design of the equipment and facilities (Manfredi and Vignali, 2015). A preventive strategy to reduce the environmental impact of the sanitation operations is the improvement of the hygienic design of the equipment.

The environmental impacts shall be evaluated by means of scientific and reliable tools, which take into account the entire lifetime of a product. Life Cycle Assessment (LCA) is the most reliable methodology to evaluate the environmental impact of a product throughout its life cycle, known as “cradle to grave” analysis. This method is regulated by the ISO 14040 (ISO 14040, 2006; ISO 14044) international series of standards.

Aim of this article is then to compare the environmental impact of a traditional machine (pressurized steam barriers system) with that of an innovative sterile water generation technology, both used for maintaining the sterility of homogenizer pistons, by considering their whole life cycle. The remainder of the paper is organized as follows. In section 2 the traditional machine and the new “NiSoPURE” system are described; afterward in section 3 we detail the full steps of the LCA methodology, according to ISO 14044 and we performed an LCA analysis of both the systems. Finally, section 4 concludes the work by summarizing the main results obtained and outlining possible future research activities.

2. Systems description

Two different machine for maintaining the sterility of homogenizer pistons produced by the company Gea
Mechanical Equipment Homogenizer located in Parma (Italy) have been considered. The first analysed model is a traditional “pressurized steam barriers system” while the second, which is called “NiSoPURE”, is an innovative sterile water generation circuit.

GEA Industrial homogenizers are machines made by two essential elements: a compression block, which allows to pump the product with a high pressure and a homogenizing valve, able to micronize dispersed particles down to the order of micrometers and nanometers, depending on product’s characteristics and the desired results.

The following sub-sections describe the two analysed systems.

2.1 “Pressurized steam barriers” model

Currently, the configuration of the "complete aseptic system" option (which includes the "sterile" fluid generation unit) requires the installation of a heat exchanger, which is fed with superheated steam (supplied by the user). This steam it condenses by bringing it to temperatures that are a compromise between the requirements of the client and the technical limitations of the static and dynamic seals. The steam is condensed in an AISI 316L brazed plate heat exchanger by a refrigerant fluid which, is specified to be demineralised water (to reduce efficiency losses due to lime scale deposits).

Compared to the traditional system, NiSoPURE permits water heating through a low environmental impact process and with much lower energy consumption.

How it works

Cold water enters the regenerative plate heat exchanger and by a system of connectors, arrives to steam injector which overheats the water. The liquid reaches thereafter an holding tube and stay for the sterilization time.

The liquid returns then to the regenerative plate exchanger, from which it started its cycle, though in the opposite way and in the exchanger clean side, where it cools down before reaching the homogenization aseptic chambers.

Thanks to its special design, the heat exchanger features a double plate separated by air chamber to eliminate the possible risk of cross contamination among the inlet water and the sterile water in case of pin-holes in the plates.

2.2 “NiSoPURE” model

Cool & Sterilize Water

NiSoPURE is the most efficient skid to sterilize and cool water used to flush homogenizers aseptic barriers.

The system is completely engineered and designed to save water and energy consumption, reducing the environmental impact as well as the costs for the final users.

NiSoPURE is based on flushing the aseptic barriers by sterilized water instead of steam. The sterile water at 40°C is used to wet the plunger surface during reciprocating movement and it allows reducing friction and temperature between seals and plunger surface. This system is the ideal high efficiency solution in the aseptic production, especially for dairy, food and beverage industries.

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Thanks to its special design, the heat exchanger features a double plate separated by air chamber to eliminate the possible risk of cross contamination among the inlet water and the sterile water in case of pin-holes in the plates.

Main specifications of both the technologies are summarized in Table 1.

<table>
<thead>
<tr>
<th>Technical Data</th>
<th>Unit</th>
<th>Pressurized steam barriers system</th>
<th>NiSoPURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>kW</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Water consumption</td>
<td>Kg/h</td>
<td>2000</td>
<td>150</td>
</tr>
<tr>
<td>Steam consumption</td>
<td>Kg/h</td>
<td>165</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 1: Technical data of the two machines

3 Life cycle assessment

Life Cycle Assessment is a methodology useful to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment. The aim is to assess the impact of the energy and materials used and the releases to the environment and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product process or activity, encompassing, extracting and processing raw materials; manufacturing; transportation and distribution; use and
final disposal. A LCA consists in four different steps, defined by ISO 14040 [4] and ISO 14044 [5] (Figure 3).

![Life cycle assessment framework](adapted from ISO 14040)

### 3.1 Goal and scope definition

The goal of this study is to compare the environmental impacts of two different equipment used for maintaining the sterility of homogenizer pistons and to evaluate the critical aspects of their life cycles.

#### 3.1.1 Functional Unit

The purpose of the Functional Unit (FU) is to provide a reference unit, for which the inventory data are normalized (ISO 14040, 2006). The functional unit is essential since it facilitates the comparison of alternative products and services (ISO 14044, 2006). The functional unit adopted in this analysis is one hour of machine operation. The lifespan of the homogenizer has been assumed of 30 years.

#### 3.1.2 System boundary

In order to quantify the impact of the analysed product, the system boundaries shall be determined. The adopted boundary systems in this case are those proposed by the Product Category Rules (PCR) basic module, general purpose machinery, version 2.5, which are also reported in Figure 4.

Following the PCR (2013), the equipment life cycle is divided in three main phases.

The first phase is called “upstream processes” and includes the following processes: the production of virgin and recycled raw materials, the production and manufacturing of the components, the activities of assembly and testing at the production plant and the packaging.

The “core processes” are referring to the machine use phase and include steam production, electricity generation, steam and electricity use during the use phase.

The “downstream processes” include the end of life management activities of the machine after the estimated life span use.

#### 3.2 Life cycle inventory analysis

The life cycle inventory analysis quantifies the resources use, the energy use, and the environmental releases associated with the system being evaluated by means of a mass and energy balance of each FU (ISO 14040, 2006).

All primary data were gathered from Gea Mechanical Equipment Homogenizer personnel thanks to a questionnaire and personal interviews. Ecoinvent database v3.1. (Swiss Centre for Life Cycle Inventories, 2010) has been used as source of secondary data, by considering data referring to the Italian context when available, otherwise, to the European situation.

As regard to the upstream process, the cut off applied to the gross weight of material has been set at 99% as required by the PCR basic module (2013).

#### 3.2.1 Upstream processes

The bills of materials of the two equipment have been provided by the company and reported in Table 2 and Table 2.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Weight (kg)</th>
<th>%</th>
<th>Weight /functional unit (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 316 L. Steel</td>
<td>9,299</td>
<td>53,9%</td>
<td>1,033E-04</td>
</tr>
<tr>
<td>AISI 304 Steel</td>
<td>6,307</td>
<td>36,5%</td>
<td>7,008E-05</td>
</tr>
<tr>
<td>Nikel</td>
<td>1,650</td>
<td>9,6%</td>
<td>1,833E-05</td>
</tr>
<tr>
<td>Total</td>
<td>17,256</td>
<td>100,0%</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Inventory data for materials used in manufacturing am Pressurized steam barriers system
The data collected in the Inventory analysis are the basis for the Impact Assessment phase, which aims to evaluate the potential environmental impacts of the system (ISO 14040, 2006). SimaPro version 8.2 software has been used for the analysis of the environmental burdens using the International Life Cycle Data (ILCD) impact assessment method (EC-JRC, 2011).

Impact values were calculated at midpoint level for 16 impact categories, i.e., Climate change, Ozone depletion, Human toxicity, non-cancer effects, Human toxicity, cancer effects, Particulate matter, Ionizing radiation HH, Ionizing radiation E (interim), Photochemical ozone formation, Acidification, Terrestrial eutrophication, Freshwater eutrophication, Marine eutrophication, Freshwater ecotoxicity, Land use, Water resource depletion and Mineral, fossil & ren resource dep.

### 4 Result and discussion

The results of impact assessment for the two machine are reported in Table 5 and Figure 4.

#### Table 3: Inventory data for materials used in manufacturing NiSoPURE

<table>
<thead>
<tr>
<th>Materials</th>
<th>Weight (kg)</th>
<th>%</th>
<th>Weight/functional unit (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 316 L Steel</td>
<td>166,620</td>
<td>41.3%</td>
<td>1,851E-03</td>
</tr>
<tr>
<td>AISI 304 Steel</td>
<td>192,388</td>
<td>47.7%</td>
<td>2,138E-03</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.784</td>
<td>0.2%</td>
<td>8,711E-06</td>
</tr>
<tr>
<td>EPDM</td>
<td>0.020</td>
<td>0.0%</td>
<td>2,222E-07</td>
</tr>
<tr>
<td>PTFE</td>
<td>0.265</td>
<td>0.1%</td>
<td>2,939E-06</td>
</tr>
<tr>
<td>LEXAN</td>
<td>43,584</td>
<td>10.8%</td>
<td>4,843E-04</td>
</tr>
<tr>
<td>Total</td>
<td>403,661</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Inventory data for materials used in manufacturing NiSoPURE

As far as the assembly and testing phases are concerned, it only the welding phase was considered. It was impossible to obtain data closely related to other operations, which were conducted in other companies, since the manufacturing company has no control on the manufacturing consumption of each product. This assumption is not completely accurate but it has been considered as acceptable since the consumption of this phase are enormously lower than those that occur during the use phase (Manfredi et al., 2015).

#### 3.2.2 Core processes

The electrical, water and steam consumptions, which occur during the use phase, have been determined by the technical sheet of Gea Mechanical Equipment Homogenizer.

#### Table 5: Absolute environmental impacts of the 2 equipment

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Traditional machine</th>
<th>NiSoPURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>kg CO2 eq</td>
<td>3,10E+01</td>
<td>1,54E+00</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>2,99E-06</td>
<td>1,82E-07</td>
</tr>
<tr>
<td>Human toxicity, non-cancer effects</td>
<td>CTUh</td>
<td>1,18E-06</td>
<td>1,25E-07</td>
</tr>
<tr>
<td>Human toxicity, cancer effects</td>
<td>CTUh</td>
<td>1,38E-07</td>
<td>1,89E-08</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>kg PM2.5 eq</td>
<td>1,71E-02</td>
<td>6,91E-04</td>
</tr>
<tr>
<td>Ionizing radiation HH</td>
<td>kBq U235 eq</td>
<td>5,67E-03</td>
<td>6,18E-02</td>
</tr>
<tr>
<td>Ionizing radiation E (interim)</td>
<td>CTUh</td>
<td>4,20E-06</td>
<td>4,62E-07</td>
</tr>
<tr>
<td>Photochemical ozone formation</td>
<td>kg NMVOC eq</td>
<td>5,44E-02</td>
<td>2,97E-03</td>
</tr>
<tr>
<td>Acidification</td>
<td>mol H+ eq</td>
<td>1,45E-01</td>
<td>7,09E-03</td>
</tr>
<tr>
<td>Terrestrial eutrophication</td>
<td>mol N eq</td>
<td>1,65E-01</td>
<td>9,90E-03</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>3,04E-04</td>
<td>3,60E-05</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>1,43E-02</td>
<td>8,71E-04</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>CTUe</td>
<td>7,41E+00</td>
<td>4,94E-04</td>
</tr>
<tr>
<td>Land use</td>
<td>kg C, deficit</td>
<td>2,79E+03</td>
<td>2,01E+00</td>
</tr>
<tr>
<td>Water resource depletion</td>
<td>m3 water eq</td>
<td>8,28E+02</td>
<td>2,74E+02</td>
</tr>
<tr>
<td>Mineral, fossil &amp; ren resource dep.</td>
<td>kg Sb eq</td>
<td>1,66E+04</td>
<td>3,92E-09</td>
</tr>
</tbody>
</table>

Lorries 16-32 t Euro5 have been considered in order to evaluate the transport of the Equipment to the customers; with an average distance of customers equal to 250 km.

#### 3.2.3 Downstream processes

Regarding downstream process, the transportation of the machine to the landfill is included in the analysis, considering a distance of 50 km from the customer to the disposal site. In this case a lorry (3.5-7.5 tons) Euro4 has been used in order to evaluate this phase. The end of life scenario considered is 100% landfill. A conservative approach has been used since the company doesn’t have the control of this phase.

#### 3.3 Method of impact assessment

The data collected in the Inventory analysis are the basis for the Impact Assessment phase, which aims to evaluate...
where the impact of pressurized steam barriers system are higher than 77 % and 24 % respectively.

![Image]

**Figure 6: Percentage contributions of all the life cycle inputs for the two extreme cases – NiSoPURE 3 a) pressurized steam barriers system 3 b)**

According to Figure 3, In both the cases, the contribution of core process (electricity, water and steam use) is the main cause of impacts in all the considered categories. In almost all the categories considered the impact of the use phase cover more than 90% of the total impact, except in 3 categories, only for NiSoPURE (Human toxicity, cancer effects, Freshwater ecotoxicity, Mineral, fossil & ren resource depletion) where the raw materials have a relevant contribution.

5 **Sensitivity analysis**

As demonstrated in the previous paragraph, the contribution of core process (electricity, water and steam use) is the main cause of impact in all the considered categories. In particular, the impact is due to the steam production.

For this reason, was carried out a sensitivity analysis about the steam production: in particular, in the new case, we assumed that the steam production is realized using the heat provided by a cogeneration system.

As can be seen from the figures the total impact is greatly reduced by using cogeneration: on average by 56% in the case of NiSoPURE and by 45% in the case of the Pressurized steam barriers system.

6 **Conclusions**

Two different equipment for maintaining the sterility of homogenizer pistons were compared using life cycle assessment methodology.

The first machine is a traditional machine (Pressurized steam barriers system) while the second uses an innovative sterile water generation circuit technology.

The impacts of the traditional machine are always higher than those of NiSoPURE for each scenario, on average of 85% in the impact categories considered, except for Water resource depletion and Mineral, fossil & ren resource depletion where the impact of pressurized steam barriers system are bigger than 77 % and 24 % respectively. The difference in terms of environmental impacts between the two machine is approximately equivalent to the percentage difference of the consumption. This is due to the fact that
the fuel consumption which occurs during the use phase is responsible for over than 85% of impacts in almost all the considered categories.

As regarding the sensitivity analysis, it was demonstrated that the total impact is greatly reduced by using cogeneration; in the case of NiSoPURE on average by 56% and by 45% in the case of the Pressurized steam barriers system.

Acknowledgments
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Swiss Centre for Life Cycle Inventories (2010). Ecoinvent Data, Dübendorf, Switzerland.
