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Editor's Letter

Presentation. -

Volume 7, Issue 2 – INQUIDE: Chemical Engineering and Development

Dear Readers and Researchers,

It is an honor to present the second issue of Volume 7 of INQUIDE: Chemical Engineering and Development, a journal that reaffirms its commitment to disseminating innovative research across various fields of engineering and related disciplines. This edition brings together five scientific contributions addressing technological, energy, and ergonomic challenges, highlighting practical solutions with industrial and environmental impact.

The first article, "Analysis of the Calorific Power of Pellets and Briquettes from Banana Pseudostem (Musa paradisiaca)", explores the energy potential of solid biofuels derived from agricultural biomass. The results demonstrate high calorific values for pellets (22.657 MJ/kg) and briquettes (22.680 MJ/kg), complying with international standards such as ENplus and NTC 2060, positioning these biofuels as viable alternatives for renewable energy generation.

The second paper, "Thermal-Hydraulic Design of a Multi-Tube Heat Exchanger for Methanol Heating", presents the detailed design of a key industrial equipment. The study calculates critical parameters such as the overall heat transfer coefficient (575.17 $W/m^2{\cdot}K$) and the required area (2.025 m^2), validating its efficiency with pressure drops below established maximum limits.

The third contribution, "Thermal-Hydraulic Design of a Finned Double-Tube Heat Exchanger for Acetone Cooling", delves into the optimization of counterflow heat exchangers. With a thermal load of 276,030 W and a cleanliness factor of 0.359, the proposed design ensures optimal performance under turbulent flow conditions, underscoring its applicability in the chemical industry.

The fourth article, "Comprehensive Ergonomic Proposal for Reducing Musculoskeletal Risks in Soap Production", addresses a critical occupational health issue. Through statistical analysis and postural assessments, risks such as forced postures (67% of workers) and manual load handling (33%) are identified, proposing practical solutions to enhance productivity and well-being in industrial settings.

Finally, the fifth study, "Application of Non-Automated Lean Strategies for Quality Improvement in Manual Assembly Processes", demonstrates how low-cost interventions, such as visual standardization and Kaizen events, can reduce defects by 3.25% in manual assembly lines, offering a replicable model for resource-limited industries.

Invitation to Readers.
This issue of INQUIDE provides a multidisciplinary perspective on real-world problems, combining scientific rigor with industrial applicability. Readers are encouraged to explore these articles, which not only enrich academic knowledge but also offer valuable tools for engineering professionals, researchers, and decision-makers.

Call for Contributors.
INQUIDE renews its invitation to the scientific community to submit original work that advances chemical engineering and related disciplines. The journal is committed to a rigorous and transparent editorial process, ensuring the dissemination of high-quality research with global impact. Interested authors are welcome to contribute to the next volume, expanding the frontiers of knowledge in an inclusive and collaborative scientific forum.

Wishing you a rewarding read, we thank you for your continued support of our journal.

Sincerely,

Francisco Javier Duque-Aldaz
Editor-in-Chief
INQUIDE
Chemical Engineering and DevelopmentAtentamente,

TABLE OF CONTENTS

Research Articles.

University of Guayaquil
Faculty of Chemical engineering
INQUIDE
Chemical Engineering and Development
https://revistas.ug.edu.ec/index.php/iqd
e–ISSN: 3028-8533 / INQUIDE / Vol. 07 / No. 02

Analysis of the calorific value of pellets and briquettes in the use of the pseudostem of Banana (Musa paradisiaca)

Análisis del poder calorífico de pellets y briquetas en el aprovechamiento del pseudotallo de Plátano (Musa paradisiaca.

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Research Articles [X] Review Articles [ ] Essay Articles [ ]

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Abstract.
Solid biofuels belong to the second generation according to the type of biomass obtained from agricultural, forestry, and industrial wastes, such as banana pseudostem, which is a lignocellulosic biomass that can be used as an alternative for the generation of renewable energy in the form of pellets and briquettes due to its energetic properties. The study aims to determine the calorific value efficiency of solid biofuels based on Plantain (Musa paradisiaca) pseudostem. The study methodology was divided into three parts: (1) obtaining and conditioning of biomass, (2) elaboration of solid biofuels, and (3) physical, proximal, and energy potential analysis of biomass and the respective ANOVA of pellets and briquettes. A high calorific value was found for the compositions 55-45% in pellet with 22,657 MJ/kg and 50-50% in briquette with 22,680 MJ/kg, complying with the parameters established in the ENplus and NTC 2060 standards, respectively.

Keywords.
Pseudostem, Biomass, Calorific value, Pellet and Briquette.

Resumen.
Los biocombustibles sólidos pertenecen a la segunda generación de acuerdo con el tipo de biomasa, obteniéndose de desechos agrícolas, forestales e industriales como el pseudotallo de plátano que es una biomasa lignocelulósica la cual se puede emplear como una alternativa para la generación de energía renovable en forma de pellets y briquetas debido a sus propiedades energéticas. El objetivo de estudio es determinar la eficiencia del poder calorífico de los biocombustibles sólidos en base al pseudotallo de Plátano (*Musa paradisiaca)*. La metodología de estudio se dividió 3 partes: (1) Obtención y acondicionamiento de la biomasa, (2) elaboración de Biocombustibles Sólidos y (3) el análisis físico, proximal, potencial energético de la biomasa y el ANOVA respectivo de pellet y briqueta. Encontrándose un alto poder calorífico para las composiciones 55-45% en pellet con 22,657 MJ/Kg y 50-50% en briqueta con 22,680 MJ/kg, cumpliendo con los parámetros establecidos en las normas ENplus y NTC 2060 respectivamente.

Palabras clave.
Pseudotallo, Biomasa, Poder Calorífico, Pellet y Briqueta.

1. Introduction

Ecuador is a country that produces large amounts of biomass and lignocellulosic waste per year, which are not fully used in the agricultural area, even though biomass is of great importance in the generation of clean energy since it is explored as an alternative raw material for the production of solid biofuels. Therefore, biomass is an available resource, which has advantages such as its ease of combustion, cellulose content and carbon neutrality. [1]

According to the Bioenergy Atlas of Ecuador using the ESPAC database, in 2012 it had a productivity of 559 319 tons/year, where 372 576 t/year corresponds to field residues (leaves, pseudostem), from which a Lower Calorific Value (PCI) of 4,180 TJ/kg was obtained. However, according to the INEN in 2022, Ecuador registered 133,145 h of planted area, giving a harvest of 114,526 h, obtaining a production of 857,561.89 metric tons [2]. It is estimated that from a banana plant weighing around 100 kg, 88% is obtained, which represents the total residues and the bunch 12%, giving a ratio between crop residues and the bunch is 2:1 [3], [4]. The lignocellulosic residues generated are the parts of the crops of plant species discarded in the harvest period [5], which are not used for consumption, so in the agricultural sector 1.44 MMt of annual biomass are estimated, however, in the forestry sector 0.22 MMt/year are produced. [6]

Our country has a great demand for the export of green bananas, which comes from the gender *Muse* of the family *Musaceae,* of the species *paradisiaca L*. It is a large herbaceous plant, which is composed of a rhizome, a pseudostem, leaves, flowers and fruit (cluster). [7]

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Approximately to obtain a ton of green bunches, 150 kg of rachis was produced, 480 kg of leaves and 3 tons of pseudostem, so these residues are used as fertilizer and animal feed. [8]

The pseudostem that occurs in large amounts of residual biomass. It is a stem formed by wide pods, its size varied from 3.5 to 6 m and weighs about 50 kg. This structure is composed of lignocellulosic compounds such as: Cellulose, lignin, hemicellulose and other chemical compounds (K, Na, Ca, Mn, P). Due to its properties, it can be used as biomass for energy generation, through the production of biofuels and thus contribute to the reduction of emissions of gases that pollute the environment. Currently, Ecuador has been engaged in adopting renewable energy as a regular part of its energy supply, with the use of biomass accounting for 1.99% of electricity production. [9]

This research article discusses the use of biomass of *Musa paradisiaca* for the production of solid biofuel in the form of pellets and briquettes, to reduce the pollutants produced by fossil fuels by choosing this replacement alternative to also reduce soil erosion, desertification, forest and crop degradation since they provide clean combustion. The quality standards established in the Enplus and NTC 2060 standards respectively will be used. In addition, ASTM 3172-89 was employed for proximal biomass and solid biofuel analyses. Therefore [10]The objective of the study is to determine the efficiency of the calorific value of solid biofuels based on the pseudostem of Banana (*Musa paradisiaca).*

1.1. Banana Pseudostem

The pseudostem weighs close to 50 kilograms and its length ranges between 3.5 and 7.5 meters, its main function being to support the leaves that emerge in the upper part and the cluster. These leaves, of a dark green tone and considerable extension, measure about 2 to 4 meters in length by 1.5 meters in width. Their structure resembles a tree trunk, is herbaceous in nature and usually has a robust and thick appearance due to the accumulation of plant fibers. Unlike trees, plane trees do not have a solid wooden trunk, instead, the pseudostem is composed of leaves arranged in concentric layers, which overlap each other. The pseudostem also serves the function of storing nutrients and water for the growth of the plant. [11] [12]

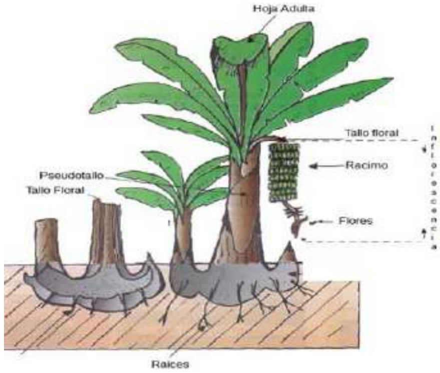

Figure 1 Banana Plant. Fountain: *[13].*

Banana cultivation in Ecuador is 128. 861 hectares planted, which is distributed in 21 provinces as shown in Figure 2, indicates that banana production at the national level was 763,455 tons.

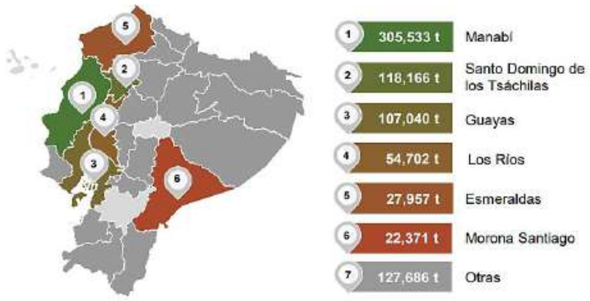

Figure 2 Production distribution. Fountain:. [14]

In contrast, in 2022 it was recorded in 133,145 hectares planted, as can be seen in Figure 3, the third place in planted area is obtained, achieving a production of 857,561.89 metric tons and a yield of 7.49 tonnes / hectares, which is the fourth place in permanent crops in Ecuador. [2] [15].

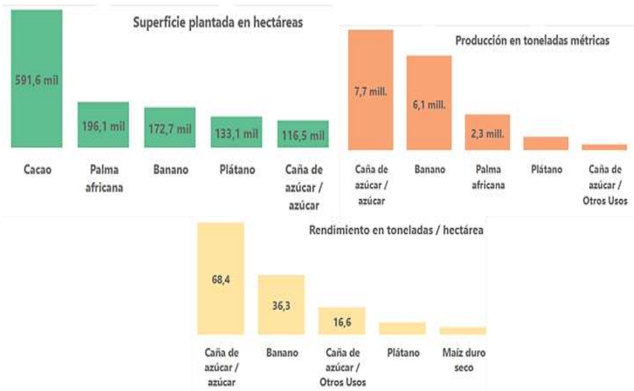

Figure 3 Banana planted area in Ecuador 2022. Fountain:. *[2]*

1.2. Biofuel

They are fuels that are manufactured with biomass, which allows greenhouse gas emissions to be reduced, only if their processes are sustainable, that is, they emit a small carbon footprint. In the generation of energy by combustion, the biomass used must have low percentages of lignin, in order to produce smaller amounts of carbonaceous waste, otherwise thermal degradation will produce large amounts of them. These biofuels are classified according to their generation: [1]

- First-generation biofuels use biomass from food agricultural crops.
- The second generation uses lignocellulosic biomass from forestry, agricultural and urban waste.
- The third generation, its biomass is from inedible species.
- Finally, the fourth generation is made from genetically modified microorganisms. [16]

Biofuels are also divided according to their status into: Liquids (Bioethanol, biodiesel, biooils), Solids (Pellets, chips, briquettes, coal) and Gaseous (biogas, biomethane, biohydrogen) [17]. This research focuses on solid biofuels (pellets and briquettes) that belong to the second generation, which allows a zero carbon footprint, because their raw material is lignocellulosic waste, which is a biological source not fully explored, which would be a great biomass alternative for the production of biofuels [18].

1.3. Solid Biofuels

Solid biofuels are forms of fuel made from organic material of plant or animal origin that can be used in different applications for power generation. They are acquired through physical methods such as compression, chipping, or crushing. Specifically, in the generation of electrical and thermal energy, solid biofuels produced from the remains of biomass from forestry or agro-industrial operations are used. The relevance of solid biofuels lies in their great capacity to meet the energy needs related to the increase in population. The use of solid biofuels will make it possible to replace fossil fuels in the generation of electricity and heat, while reducing the disadvantages caused by traditional fuels. Within the range of solid biofuels are chips, briquettes and pellets, which are compact forms with a high heat capacity. [19] [16] [20]

The main components used in the production of solid biofuels are derived from lignocellulosic materials, which come from agriculture or forestry, so waste from agribusiness has multiple potential uses, including the creation of organic fertilizer or the manufacture of biofuels. [16]

Table 1.- Types of Solid Biofuels.

Types	Source/source	Use
Splinter	Agricultural and forestry residues. Woody crops. Agri-food waste.	Bakery ovens, ceramics, in small industries, homes and heating.
Charcoal	Wood and plant residues.	Domestic.
Pellet & Briquette	Wood Industry. Example: Teak, alfalfa, etc.	Fuel: in industrial and large areas.

Note: Information obtained from. Fountain:. [21] [22]

Figure 4 Types of Solid Biofuels. Fountain:. *[21]*

Here are some characteristics of pellets and briquettes.

1.3.1. Pellets

They are cylindrical biofuels, of different types of biomass on which their color will depend (vegetable, animal, agro-industrial and urban solid waste), where their range of dimensions is: diameter of 6-8 mm and 3.15-40 mm in length. Where the fundamental property is calorific value ≥ 16,5 . Other properties are its moisture percentage of $\frac{MJ}{Kg}$ ≤10% This value determines the amount of energy that the pellets will produce when they are subjected to combustion, and in other words, if the water content is high, in combustion it will be eliminated first and then heat will be produced, obtaining a low calorific value. In addition, the ash must be 0.7% and a bulk density of [23]≤600 $\frac{Kg}{m^3} -$ 750 $\frac{Kg}{m^3}$, these properties are in accordance with the En Plus Standard. [24]

Figure 5 Pellets. Note: Pellets produced from rice husks. Fountain:. *[25]*

1.3.2. Briquettes

They are solid blocks of varied shapes (the most commonly used rectangular and round), which have a diameter of more than 5 cm and a length between. Where the fundamental property is calorific value from 12,500-21,000 $\frac{MJ}{Kg}$. Other properties are its moisture percentage of 2,5% and ash 30% these properties are according to the Colombian Standard. [26]

Figure 6 Briquettes. Note: Briquettes of different materials and shapes. Fountain:. *[27]*

1.4. Biomass

It is a type of renewable energy that is obtained from organic matter, such as agricultural waste, forestry, food, manure, among others. This organic matter can be used as fuel for the generation of heat, electricity and biofuels (Tepale Gómez, 2020). In addition, biomass is a renewable energy source, as it comes from biological organisms that can be grown and regenerated in a relatively short period of time. This makes it a sustainable option for energy production, unlike fossil resources that are limited and cannot be regenerated. [20] [28]

Another benefit of biomass is that its processing and use does not require complex technologies. It can be used directly in the form of firewood, pellets or briquettes, or it can be converted into different forms of energy such as electricity, heat or biogas through combustion, gasification or fermentation processes. [6]

The use of biomass as an energy resource has several advantages compared to oil, coal and gas: [6]

-Improvement of the socio-economic situation of rural areas: The use of agricultural residues to generate energy from biomass can generate employment and income in rural areas, boosting the economic development of these areas. [6]
-Reduction of polluting emissions: By using biomass instead of fossil fuels, emissions of pollutants such as sulfur, particulate matter, carbon monoxide (CO), methane (CH_4) and nitrogen oxides (NOx) are reduced, which has a positive impact on air quality and public health. [6]
-CO_2 neutral cycle: Biomass has the advantage of being a renewable resource and its combustion does not contribute to the greenhouse effect significantly, since the carbon dioxide (CO_2) released during burning is the same that was absorbed by plants during their growth. This helps reduce greenhouse gas emissions and mitigate climate change. [29]
-Potential of Latin America and the Caribbean: These regions have a large amount of natural and agricultural resources, which positions them as potential producers of biomass. The development of the bioeconomy in these areas can boost their socio-economic development, as well as promote energy security and reduce dependence on fossil fuels. [6]

In summary, the use of biomass as an energy resource has several advantages, both socio-economically and environmentally, which makes it an interesting and sustainable alternative compared to traditional fossil fuels. [6]

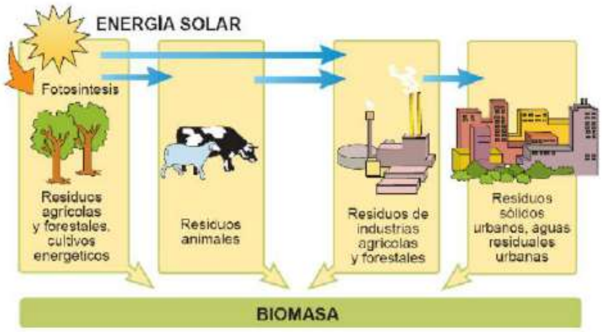

Figure 7 *Biomass. Fountain:* [21].

1.5. Features

1.5.1. Moisture Content

For the test, the procedure of the ASTM D-3173 standard was followed, in which the formula was used:

$$\%H = \frac{A - B}{A} * 100 \qquad (1)$$

Where:

A: grams of initial sample in g.
B: grams of final sample in g.

1.5.2. Ash Content

The ash content of a mass is determined according to the amount of minerals it contains and for this the following formula is used. [30]

$$\%C = \frac{m_3 - m_1}{m_2 - m_1} * 100 \qquad (2)$$

m_1: Empty crucible dough and lid.
m_2: Crucible mass and lid +1 g sample.
m_3: Crucible mass and lid + heated muffle sample.

1.5.3. Density

For this test, the biofuels were weighed and their determined volume was obtained, and then the following equation was applied:

$$d = \frac{m}{v} \qquad (3)$$

d= density
m = mass
v =volume

1.5.4. Calorific Value

Is The amount of energy that can be obtained by burning a substance. It refers to the ability of a substance to produce heat by performing a complete combustion chemical reaction [31].Calorific value is measured in units of energy per units of mass such as joules or calories.

1.5.5. Volatile Material:

This test of the percentage of volatile material was worked according to the standard, using the following equation: [32]

$$\%MV = \left(\frac{m_2 - m_3}{m_2 - m_1} * 100\right) - h \qquad (4)$$

m_1: Empty crucible dough and lid.
m_2: Crucible mass and lid +1 g sample.
m_3: Crucible mass and lid + sample

1.5.6. Fixed Carbon

It is the subtraction of 100 and the result of the sum of the percentage of moisture, ash and volatile material [33].

$$C.Fijo = [100 - (H\% + C\% + MV\%)] \qquad (5)$$

H: Percentage of moisture.
C: Percentage of ash.
MV: Percentage of volatile material.

2. Materials and methods.

Study Area

The study area includes lot 9 of the Canaán I urbanization of the Cumandá Canton (Chimborazo-Ecuador).

2.1. Methodology

The methodology of the study is divided into 3 sections: (1) Obtaining and conditioning of biomass (raw material), (2) production of pellets and briquettes and (3) Methods of physical characterization, proximal and structural analysis and the respective anova.

2.2. Obtaining and conditioning of biomass

The choice of this biomass is based on its abundant availability as agricultural waste in Ecuador and its high content of lignocellulosic components, suitable for the production of solid biofuels. This initial step also includes an analysis of the plants' growing conditions to ensure uniformity in the samples, including data on plant age, soil conditions, and harvest time.

Samples of banana pseudostem of the Dominican and Barragañete species were collected randomly after harvest, then they were cut into a rectangular shape (2cmx5cm) and the pieces were exposed to the sun for 8 days, to reduce the moisture content. The samples were then dried by an oven at a temperature of 60°C for 12 hours in aluminum cans. Then, it was introduced into a hammer mill, in order to reduce its size, and then placed in a vibrating machine for 5 minutes, until the particles decreased to a mesh size of 0.8 mm, 0.63 mm and 0.315 mm. To finish with the conditioning of the biomass, the humidity was removed at 100°C for 6 h.

2.2.1. Chemical composition of Biomass

Proximal analysis, performed according to ASTM D3172-89 to determine cellulose, hemicellulose and lignin content. The average composition obtained was 31.27% cellulose, 15.07% hemicellulose and 23.9% lignin, which shows a high energy content suitable for use in biofuels.

2.3. Pellet and briquette production

In this stage, the biomass was homogenized with the binder according to the selected compositions where the following amounts of biomass-binder were used.

Table 2 *Compositions of Solid Biofuels*.

Composition	Amount of Biomass (g)	Amount of binder (g)	Amount of Residue (g)	Quantity of Biofuels
Pellet 50-50	26	26	2	14 Pellets
Pellet 55-45	28,6	23,4	2	13 Pellets
Pellet 60-40	31,2	20,8	3	11 Pellets
Briquettes 50-50	205	205	8	6 Briquettes
Briquettes 55-45	270,6	221,4	6	6 Briquettes
Briquettes 60-40	246	164	11	6 Briquettes

Note: Information Obtained from . [22]

With the quantities used in each composition, a compact mass was obtained by means of the pellet and briquetting machine. To finish with the drying in the environment for 72 hours of the pellets and briquettes produced.

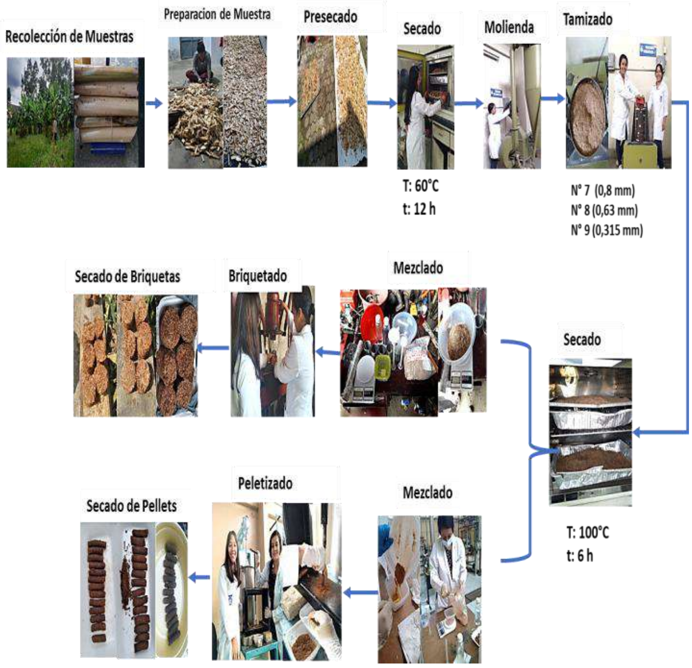

Figure 8 Flow Chart. Fountain:. *[22]*

2.4. Methods of physical characterization, proximal analysis, structural analysis and anova.

The calorific value was evaluated using a calorimetric pump under the ASTM D5865 standard. This analysis included the measurement of the energy content in MJ/kg of the samples produced in different compositions. In addition, ANOVA statistical analysis and Tukey's post-hoc test were used to determine the significance of the differences between pellet and briquette compositions

2.4.1. Physical characterization

This characterization was based on the procedures of the ASTM S3172-89 standard for moisture content for ground biomass. On the other hand, for solid biofuels, the same wet content standard was applied and their density was found. Preliminary analyses are essential to understand the composition of the pseudostem. You can include an analysis of the amount of cellulose, hemicellulose and lignin, which are key elements in the calorific value of biomass. Based on previous studies, banana pseudostem has high cellulose (between 30-60%) and lignin values, indicating its suitability as a solid biofuel

2.4.2. Proximal analysis

The characterization of the ground biomass was carried out using the ASTM D3172-89 standard, which describes the methods for determining the content of ash, volatile material and fixed carbon. For the study of the calorific value, the ASTM D240 standard was applied by the LAQUINS ESPOL laboratory.

2.4.3. Structural Analysis

The samples were sent to the LAQUINS ESPOL laboratory, for the characterization of lignin, cellulose and hemicellulose. These analyses were performed according to TAPPI T 203 and 222.

2.4.4. Anova

It is the statistical procedure used to evaluate hypotheses known as ANOVA and is used to contrast two or more averages associated with a common factor. This method is applied to the dataset, which generates variations, where it is subjected to different conditions where it is verified if it is similar or unequal. It has Null and Alternate hypotheses, which in order to reject the null hypothesis must not meet the condition that one of the means is different from the rest. And on the other hand, for the alternative hypothesis to be rejected, all the means must be equal. [34]

2.4.5. Tukey's method

The Tukey method complements the information obtained from ANOVA, allowing the comparison of the sample means obtained from an experimental trial. The Tα value is calculated from the following equation (Cajal, 2022):

$$T\alpha = q\alpha(K, N-K)\sqrt{CM_E/n_i} \qquad (6)$$

$T\alpha$ = HSD number (Honestly Significant Difference)
qα= quantiles of the Tukey distribution (table with relative significance of 0.05% equal to 95% reliability)
n = number of repetitions of the study
CME = Mean Square Error Factor represents the standard error of each average

The tukey test states that when the variation between two means is greater than the value of *The,* it is considered unequal, however, if the difference is smaller, it is considered to be statistically identical. [35]

3. Analysis and Interpretation of Results.

The physical characterization, proximal and structural analysis of the ground banana pseudostem biomass is shown in Table 3.

Table 3 Biomass Characterization Results

Parameter	Unit	Result	Method of Analysis
*Calorific value	$\frac{MJ}{Kg}$	14,44	ASTM D240
Humidity	%	4,24	ASTM D3172-89
Ash	%	6,76	ASTM D3172-89
Volatile Material	%	80,65	ASTM D3172-89
Fixed Carbon	%	8,34	ASTM D3172-89
*Lignin	%	23,9	TAPPI T 222
*Hemicelulosa	%	12,9	TAPPI T 203
*Cellulose	%	13,7	TAPPI T 203

Note: The analyses were carried out in the Laboratory of our Faculty. *Result taken from the report of the Laquins Espol Laboratory**.** Fountain: [36].

The results of the proximal analysis of the biomass from the banana pseudostem, corresponding to 4.240%, 6.761%, 80.659% and 8.3406% for the percentage of moisture, ash, volatile material and fixed carbon respectively, as well as 14.447 MJ/Kg of calorific value, which according to the En plus standard and the Colombian NTC 2060 standard is a value close to the permissible limit of energy content for the production of solid biofuels.

On the other hand, the results of the proximal analysis carried out on the biomass indicated that 23.9% lignin was obtained, representing the largest component of the banana pseudostem, followed by hemicellulose and cellulose with lower fractions with the percentages of 12.9% and 13.7% respectively. These values allowed homogeneous combinations to be obtained in the mixing stage.

Table 4 Comparison of the parameters of the results of the Pellet with the Spanish Standard.

Parameter	Unit	50%-50% 1	55%-45% 2	60%-40% 3	ENplus
*Calorific value	$\frac{MJ}{Kg}$	22,566	22,657	20,835	Meets
Humidity	%	5,190	6,888	6,403	Meets
Ash	%	3,641	3,425	4,248	Not compliant
Volatile Material	%	87,001	86,301	86,181	-
Fixed Carbon	%	2,685	3,385	3,167	-
Density	$\frac{Kg}{m^3}$	750	650	273	Turns [1 and 2]

Note: The analyses were carried out in the Laboratory of our Faculty. *Result taken from the report of the Laquins Espol Laboratory. Fountain: [36] and Authors.

Table 4 specifies the results of the proximal pellet analysis. Given that the moisture content in biofuels is an important factor since as it decreases the calorific value increases, it can be deduced that this is not reflected in the pellets obtained, since as the moisture content increases by 5.19% so does its calorific value according to compositions 50-50 and 55-45. which means that the heat released in combustion that is used to evaporate the water, does not adversely influence the calorific value. Taking into account that the composition 55-45 has 22,566 MJ/kg of BW, the pellets are considered to meet the quality parameters of solid biofuel ideal for energy production, according to the ENplus standard.

According to the Spanish Standard, the pellet density value must be greater than or equal to 600, therefore, the compositions 50-50 and 55-45 obey that condition, since they consist of a density of 750 and 650, however, $\frac{Kg}{m^3}\frac{Kg}{m^3}\frac{Kg}{m^3}$with the data obtained from the pellet ash content, no composition meets that parameter, however, the 60-40 composition has a higher percentage of ash, which can be related to the fact that the biomass contains a high content of inorganic compounds. The ash content is inversely proportional to the calorific value.

Table 5 Comparison of the parameters of the Briquette results with the NTC Standard.

Parameter	Unit	50%-50%	55%-45%	60%-40%	NTC Standard
*Calorific value	$\frac{MJ}{Kg}$	22,680	19,907	19,416	Meets
Humidity	%	5,005	4,357	4,132	Not compliant
Ash	%	2,736	3,613	4,512	Meets
Volatile Material	%	85,576	87,425	87,4227	Not compliant
Fixed Carbon	%	6,682	4,603	3,882	Meets
Density	$\frac{Kg}{m^3}$	569,4	592,9	376,7	-

Fountain:. [36] [22]

As can be seen in table 5, the results obtained from the physicochemical tests: the moisture content is linked to the energy content, in this case it is visualized that the lower the moisture content the lower the calorific value is obtained, so in the 60-40 composition the higher moisture content and the same higher energy content was obtained. therefore, it is considered that this characteristic does not affect the calorific value in this type of biofuel, which includes that the composition 50-50 with 22,680 $\frac{MJ}{Kg}$ has a higher energy content with respect to the proportions of 55-45 and 60-40 with 19,907 $\frac{MJ}{Kg}$ and 19,416 respectively, to a certain extent although the percentages of moisture content are not within the permissible limits of the NTC 2060 standard, your PC, if it is, as well as the ash contents. $\frac{MJ}{Kg}$

The proximal analysis of each briquette indicated that the composition of 55-45 has a higher density of 592.9 $\frac{Kg}{m^3}$, followed by the 50-50 ratio with 569.40 and 60-40 with a lower value of 376.7. $\frac{Kg}{m^3}\frac{Kg}{m^3}$

4. Discussion

4.1. Comparison of calorific value between pellet and briquette

Table 6 Ideal solid biofuel.

Parameter	Unit	Pellet 50%-50%	Pellet 55%-45%	Briquette 50%-50%	Briquette 55%-45%
Calorific value	$\frac{MJ}{Kg}$	22,566	22,657	22,680	19,907

Fountain:. [36]

In the pellets of the 55-45 composition, a higher calorific value (CP) was obtained, but in the 50-50 it decreased, giving 22.657 $\frac{MJ}{Kg}$ and 22.566 respectively. On the other hand, in briquettes it gave a high energy content in the composition of 50-50 with 22.680, while in 55-45 it was reduced to 19.907$\frac{MJ}{Kg}\frac{MJ}{Kg}\frac{MJ}{Kg}$. Therefore, it is considered that the use of the banana pseudostem as biomass for energy use gave an optimal result in the briquette of composition 50-50, according to the PC.

It should be considered that the 55-45 pellet configuration does not have significant variation in the CP compared to the 50-50 briquette composition, so it was considered that the *Musa paradisiaca* is suitable as a raw material for the production of solid biofuels in the aforementioned proportions.

Table 7 Variance of pellet calorific value results.

Groups	Account	Sum	Average	Variance
Composition 50-50%	3	67,697	22,56566667	1.23333E-05
Composition 55-45%	3	67,972	22,65733333	1.23333E-05
Composition 60-40%	3	62,506	20,83533333	1.23333E-05

Fountain:. [22]

Table 8 *ANOVA.*

Origin of the variations	Sum of squares	Degrees of freedom	Average of squares	F	Probability	Critical value for F
Between groups	6,322140222	2	3,161070111	256302,982	1,60E-15	5,14325285
Within the groups	7.4E-05	6	1.23333E-05			
Total	6,322214222	8				

Fountain:. [22]

Decision

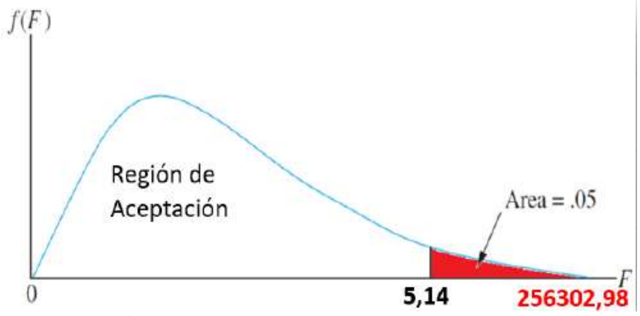

Figure 9 Distribution F. Source: . *[37]*

Figure 9 indicates that the value corresponding to F exceeds the critical value of 5.14 according to the acceptance zone, and that there is a significant difference, the null hypothesis was rejected.

Table 9 Try Tukey a Pellets according to their calorific value.

Compositions A (50-50); B(55-45); C(60-40)	Sample difference	Decision
µA - µB	0,09	Significant
µA - mC	1,73	Significant
µB - mC	1,82	Significant

Note: µ= sample average in absolute value. Fountain:. [22]

According to the Tukey test, the values of the sample difference expressed in absolute value are compared with Tukey's Tα= 0.009, showing a significant difference in more than one test, which indicates that the null hypothesis is rejected and the alternate hypothesis is accepted.

Table 10 *Variance of briquette calorific value results.*

Groups	Account	Sum	Average	Variance
Composition 50-50%	3	68,042	22,681	9.33333E-06
Composition 55-45%	3	59,721	19,907	9E-06
Composition 60-40%	3	58,248	19,416	1E-06

Fountain:. [22]

Table 11 ANOVA.

Origin of the variations	Sum of squares	Degrees of freedom	Average of squares	F	Probability	Critical value for F
Between groups	18,59235622	2	9,296178111	1442510,397	8.99506E-18	5,14325285
Within the groups	3.86667E-05	6	6,44E-06			
Total	18,59239489	8				

Fountain:. [22]

4.2. Decision

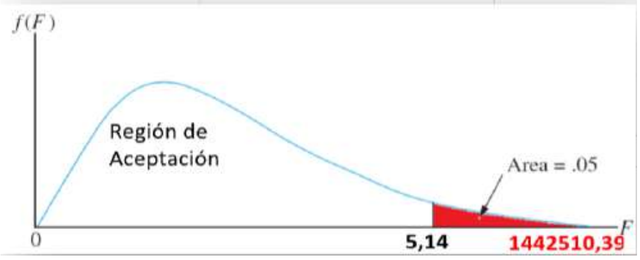

Figure 10 Distribution F. Fountain:. [37]

In the *Figure 10*, the distribution of the F-values with a significant probability of 0.05 is shown. The null hypothesis is rejected, since the value of F is outside the acceptance region, indicating a significant difference between the values of calorific value of the briquettes.

Table 12 Try Tukey Pellets according to their calorific value.

Compositions A (50-50); B(55-45); C(60-40)	Sample difference	Decision
µA - µB	2,77	Significant
µA - mC	3,26	Significant
µB - mC	0,49	Significant

Note: µ= sample average in absolute value. Fountain:. [22]

In *Table 12,* they show that the values of sample difference given in absolute value are higher compared to the value of Tα= 0.006, which indicates that all compositions have a significant difference approving the alternative hypothesis, which specifies that at least one value must be different from the others, contrary to the null hypothesis that expresses that the difference of the values of the means must be equal, that is, they do not show significant difference, to be accepted.

5. Conclusions.

Banana plant waste is a raw material generated in large quantities in Ecuador. In this research, the efficiency of solid biofuels was determined from calorific value analysis, resulting in both pellets and briquettes being within the regulations for solid biofuels, with a 22,657 MJ/Kg and 22,680 MJ/Kg respectively. Therefore, it is evident that the solid biofuel with the highest calorific value is the briquette based on banana pseudostem, where 5% humidity and a production yield of 98.04% were achieved. Therefore, the results show that the banana pseudostem is viable and a great biomass alternative for the production of briquettes, because from the ground biomass 14.44 of $\frac{MJ}{Kg}$ calorific value was reached, which stands out because without the application of a binding substance it complies with the NTC 2060 Standard where it establishes that for it to be classified as briquette its calorific value must be between the range of 12.5 - 21 $\frac{MJ}{Kg}$. In addition, this research marks the beginning of more studies on the waste from the banana plant, in which

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100% biomass is used without the need for binders, where the amount of waste from this plant could be reduced, for the generation of energy in a renewable way and with a zero carbon footprint. which contributes to the care of the environment.

6.- Author Contributions (Contributor Roles Taxonomy (CRediT))

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5. Resources: Sandra Peña
6. Supervision: Sandra Peña
7. Validation: Darla Vaca
8. Visualization: Sandra Peña
9. Writing - original draft: Nahir Alondra Pérez and Sandra Peña
10. Writing - proofreading and editing: Sandra Fajardo
11. Review: Eddie Zambrano and Pablo Fajardo

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Thermo-hydraulic design of a multi-tube heat exchanger for methanol heating.

Diseño térmico-hidráulico de un intercambiador de calor multi-tubo para el calentamiento de metanol.

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Research Articles [X] Review Articles [ ] Essay Articles [ ]

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Abstract.
A type of heat exchanger that has gained adequate attention owing to its simplicity, robustness and extensive variety of applications is the multi-tube heat exchanger. In the present work a multi-tube heat exchanger was designed form the thermo-hydraulic point of view, in order to heat a methanol stream to 60 ºC using water condensate as the heat transfer agent. To design this equipment, a classical, well known calculation methodology was employed, where several important design parameters were calculated such as the overall heat transfer coefficient (575.17 W/m^2.K), the required heat exchange area (2.025 m^2) and the Log Mean Temperature Difference (38.02 ºC). The calculated pressure drop values of the methanol and water streams were 3,257.66 Pa and 752.88 Pa, respectively, which are lower than the maximum limits set by the heat exchange service for both streams. The designed multi-tube heat exchanger will present a total length of 5.76 m.

Keywords.
Heat exchange area, multi-tube heat exchanger, pressure drop, tube length.

Resumen.
Un tipo de intercambiador de calor que ha ganado adecuada atención debido a su simplicidad, robustez y extensa variedad de aplicaciones es el intercambiador de calor de multi-tubo. En el presente trabajo, un intercambiador de calor de multi-tubo fue diseñado desde el punto de vista térmico-hidráulico, con el fin de calentar una corriente de metanol hasta 60 ºC usando agua condensada como agente de transferencia de calor. Para diseñar este equipo, se empleó una metodología de cálculo clásica y bien conocida, donde varios parámetros de diseño importantes fueron calculados tales como el coeficiente global de transferencia de calor (575,17 W/m^2.K), el área de transferencia de calor requerida (2,025 m^2) y la Diferencia de Temperatura Media Logarítmica (38,02 ºC). Los valores de caída de presión calculados de las corrientes de metanol y agua fueron 3 257,66 Pa y 752,88 Pa, respectivamente, los cuales están por debajo de los límites máximos fijados por el servicio de intercambio de calor para ambas corrientes. El intercambiador de calor multi-tubos diseñado presentará una longitud total de 5,76 m.

Palabras clave.
Área de intercambio de calor, intercambiador de calor multi-tubo, caída de presión, longitud del tubo

1. Introduction

Heat exchangers are thermal apparatuses aimed for the efficient heat exchange between two fluids, whether the fluids are in direct contact, mixed, or separated by a thin solid wall (unmixed). They are proposed in a range of sizes, shapes, and construction types depending on the industrial purpose. The performance of heat exchangers can be upgraded by suitable design and establishing optimal operating specifications. Therefore, the continued improvement of different design aspects and the performance characteristics of heat exchangers is the main target of both researchers and manufacturers who are working in this field [1].

Heat exchanger thermal design heavily rely on physical properties for obtaining heat transfer coefficients and therefore performing design calculations such as heat exchange area and overall heat transfer coefficients [2].

Among the common tubular heat exchanger used today in many industries are the multi-tube heat exchangers (MTHE) which comprise several smaller diameter pipes aligned in parallel within a larger diameter outer shell (Figure 1). In welded designs, the inner tubes and shell are welded to the tube sheets [3].

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Fig. 1. An overview of a multi-tube heat exchanger. Source: [3].

Appropriate for heating, cooling, sterilization and thermal treatment, MTHE can process a wide variety of liquids (dairy, juices, sauces, beverages, processed food) from low viscosities up to medium/high viscosities, depending on the purpose. They can also be used for products with particles when fitted with a conical tube-sheet [3].

Due to their assembly with distinctive configurations of inner tubes bundled inside an outer shell, MTHE generate a significant heat exchange area in a reasonably small volumetric space. This configuration makes this heat exchanger valuable for handling an extensive range of flowrates. Among the main features that these types of heat exchanger present are [3]:

1) The use of thermal expansion bellows to absorb difference of expansion.
2) Conical tube sheet for liquids containing particles.
3) Baffles are commonly installed for mechanical strength and better heat transfer on the shell side.
4) Product side can be scrutinized by eliminating bends between units. All inner tubes are observable.
5) Low cost, straightforward maintenance with the only requisite of periodically replacing gaskets on connections.

According to [4] these units are usually constructed by specialized companies, and there are several patent-protected closure systems. They can be an economical solution in cases where the flowrates are relatively small and it is required to apply a countercurrent configuration.

They are restricted to a few inner tubes because for higher sizes this type of assembly becomes challenging. They are not a competitive solution against the shell and tube heat exchangers (STHE), although they are cheaper than STHE [5], and are limited to applications where the required heat transfer area is less than 10 or 15 m^2 [4].

Efficient and accurate thermal analysis of MTHE provides a basis for successful design [6]. The primary attention of MTHE design is the efficiency of heat dissipation by solid conduction and forced flow convection. A good MTHE should have an optimum multi-tube configuration to dissipate as much heat as possible [6].

There are few studies reported in the open published literature where a multi-tube heat exchanger is designed or sized. According to this, in [7] a co-axial multi-tube heat exchanger (CMTHE) is proposed and integrated with a 50 kW geothermal Organic Rankine Cycle (ORC), in order to perform tow field tests to examine the response of the ORC system subject to changes applied to the CMTHE. In this study the working fluid in the tube-side of the heat exchanger is pure water with a flowrate of 13 tons per hour, while in the shell side the working fluid is geothermal hot water (~ 120 ºC). The CMTHE used in this work has a total length of 11 m, an effective heat transfer area of 18.6 m^2, and the internal and external diameter of the tubes are 10.7 mm and 12.7 mm, respectively. Other authors [1] investigated the influence of several operating parameters on the performance of concentric finned tube and bare multi-tube hairpin heat exchangers. A computer program was written and developed to carry out thermo-hydraulic computations using the MATLAB. The developed MATLAB code was then verified for reliability and precision against some of the existing and acceptable designs of single-finned tube and bare multi-tube hairpin heat exchangers. The existing counter flow bare multi-tube heat exchanger evaluated in this study used fresh water on the shell side, and oily water on the tube side with a mass flowrate of 6,622 kg/h for both streams; the internal and external diameters of the tubes are 17.95 mm and 22.21 mm, respectively; the number of internal tubes is 7; the inlet temperatures of the tube side fluid (oily water) and the shell side fluid (fresh water) were 247 ºC and 80 ºC, respectively; and the total length of the heat exchanger is 60.96 m. Finally, the allowable pressure drops for both fluid streams were 137,895.15 Pa, while the actual pressure drop of the oily water in the tube side was 22,063.22 Pa. Likewise, [6] proposed a general mathematical model for the optimal heat-transfer efficiency design of compact multi-tubular heat exchangers using topology optimization concepts. For optimization objectives, the multi-tubular configuration was transformed into an equivalent cellular material distribution within a given cross-section, which was then exemplified by two design variables: local relative cell density and cell size. Also, in [8] a numerical performance investigation of a phase change material-based multi-tube heat exchanger incorporated with two new fin configurations was carried out, in order to enhance the heat transfer. Finally, in a comprehensive experimental and numerical investigation, [9] studied smooth and rectangular-finned double pipe and multi tube heat exchangers with the prospect of presenting the most optimum operating conditions.

Certain chemical plant erected in Cuba needs to heat a liquid methanol stream to 60 ºC using hot water (condensate), and for that a multi-tube heat exchanger was proposed because the flowrates of the fluids are relatively small, there is enough space availability and there is limitation of budget. In this context, in the present paper a MTHE is designed applying the methodology reported in [10], where several important parameters are determined such as the overall heat transfer coefficient, the required heat exchange area, the length of the heat exchanger, and the pressure drop of both fluids.

2. Materials and methods.

2.1. Problem statement.

It's required to preheat 2,000 kg/h of a liquid methanol stream from 30º C to 60 ºC using 3,000 kg/h of hot water (condensate) available at 90 ºC. For that, a multi-tube heat exchanger was proposed with a shell internal diameter of 72.1 mm, equipped with seven inner tubes with an internal and external diameter of 14 and 16 mm, respectively. The pressure drops for the methanol and water stream must not exceed 3,500 and 1,000 Pa, respectively. The material of the tubes is carbon steel; the fluids will flow in a countercurrent arrangement inside the heat exchanger, while the fouling factors for methanol and water are 0.000352 and 0.000088 $K.m^2/W$, respectively [11].

According to suggestions reported by [12], the cold fluid (methanol) will be located on the tube side, while the hot fluid (water) will be located on the shell side. The internal diameters of the nozzles in the tube side and shell side are 32 mm and 50 mm, respectively, and the wall thickness of the tubes is 2 mm. It's necessary to know the tube length required by this multitube heat exchanger, as well as the pressure drops of both streams, for the requested heat transfer service. The calculation methodology proposed by [10] should be employed in this work to design the MTHE.

2.2. Calculation of the tube length.

Step 1. Definition of the initial data available:

- Methanol mass flowrate (m_c).
- Water mass flowrate (m_h).
- Inlet temperature of methanol (t_1).
- Outlet temperature of methanol (t_2).
- Inlet temperature of water (T_1).
- Internal diameter of shell (D_i).
- Internal diameter of tubes (d_i).
- External diameter of tubes (d_e).
- Internal diameter of the tube side nozzle (d_N).
- Internal diameter of the shell side nozzle (D_N).
- Thermal conductivity of tube material (carbon steel) (k_t).
- Tube wall thickness (e_t).
- Fouling factor of methanol (R_c).
- Fouling factor of water (R_h).
- Number of internal tubes (n).
- Maximum allowable pressure drop for methanol [$\Delta P_{c(a)}$].
- Maximum allowable pressure drop for water [$\Delta P_{h(a)}$].

Step 2. Average temperature of methanol ($\bar{t}$):

$$\bar{t} = \frac{t_1 + t_2}{2} \quad (1)$$

Step 3. Physical parameters of methanol at the average temperature determined in step 1:
The following parameters must be defined for the methanol at the average temperature:

- Density (ρ_c) [kg/m³].
- Viscosity (μ_c) [Pa.s].
- Heat capacity (Cp_c) [J/kg.K].
- Thermal conductivity (k_c) [W/m.K].

Step 4. Heat duty (Q):

$$Q = \frac{m_c}{3{,}600} \cdot Cp_c \cdot (t_2 - t_1) \quad (2)$$

Step 5. Heat capacity of water (Cp_h) at the inlet water temperature (T_1).

Step 6. Outlet temperature of water (T_2):

$$T_2 = T_1 - \frac{Q}{\frac{m_h}{3{,}600} \cdot Cp_h} \quad (3)$$

Step 7. Average temperature of water ($\bar{T}$):

$$\bar{T} = \frac{T_1 + T_2}{2} \quad (4)$$

Step 8. Physical parameters of water at the average temperature determined in step 6:

The following parameters must be defined for the water at its average temperature:

- Density (ρ_h) [kg/m³].
- Viscosity (μ_h) [Pa.s].
- Thermal conductivity (k_h) [W/m.K].

Step 9. Cross section area of tube (a_t):

$$a_t = n \cdot \frac{\pi \cdot d_i^2}{4} \quad (5)$$

Step 10. Velocity of methanol on the tube-side (v_c):

$$v_c = \frac{\frac{m_c}{3{,}600}}{\rho_c \cdot a_t} \quad (6)$$

Step 11. Reynolds number of methanol (Re_c):

$$Re_c = \frac{d_i \cdot v_c \cdot \rho_c}{\mu_c} \quad (7)$$

Step 12. Prandtl number of methanol (Pr_c):

$$Pr_c = \frac{Cp_c \cdot \mu_c}{k_c} \quad (8)$$

Step 13. Nusselt number of methanol (Nu_c):
As stated by [10], the Nusselt number depends on the value of the Reynolds number of the fluid inside the heat exchanger. Accordingly:

- Laminar region ($Re_c \leq 2{,}300$):

$$Nu_c = 1.86 \cdot Re_c^{0.33} \cdot Pr_c^{0.33} \cdot \left(\frac{d_i}{L}\right)^{0.33} \quad (9)$$

- Intermediate region ($2{,}300 < Re_c < 8{,}000$):

$$Nu_c = (0.037 \cdot Re_c^{0.75} - 6.66) \cdot Pr_c^{0.42} \quad (10)$$

- Turbulent region ($Re_c \geq 8{,}000$):

$$Nu_c = 0.023 \cdot Re_c^{0.8} \cdot Pr_c^{0.33} \quad (11)$$

Step 14. Convective heat transfer coefficient for methanol (h_c):

$$h_c = \frac{Nu_c \cdot k_c}{d_i} \quad (12)$$

Step 15. Convective heat transfer coefficient for methanol based on the tube outer surface area (h_{co}):

$$h_{co} = h_c \cdot \frac{d_i}{d_e} \quad (13)$$

Step 16. Flow cross-section in the shell (a_{shell}):

$$a_{shell} = \frac{\pi}{4} \cdot (D_i^2 - n \cdot d_e^2) \quad (14)$$

Step 17. Velocity of water on the shell (v_h):

$$v_h = \frac{\frac{m_h}{3{,}600}}{\rho_h \cdot a_{shell}} \quad (15)$$

Step 18. Hydraulic diameter for heat exchange (d_h):

$$d_h = \frac{D_i^2 - n \cdot d_e^2}{n \cdot d_e} \quad (16)$$

Step 19. Reynolds number of water (Re_h):

$$Re_h = \frac{d_h \cdot v_h \cdot \rho_h}{\mu_h} \quad (17)$$

Step 20. Prandtl number of water (Pr_h):

$$Pr_h = \frac{Cp_h \cdot \mu_h}{k_h} \quad (18)$$

Step 21. Nusselt number of water (Nu_h):

- Laminar region ($Re_h \leq 2{,}300$):

$$Nu_h = 1.86 \cdot Re_h^{0.33} \cdot Pr_h^{0.33} \cdot \left(\frac{d_h}{L}\right)^{0.33} \quad (19)$$

- Intermediate region ($2{,}300 < Re_h < 8{,}000$):

$$Nu_h = (0.037 \cdot Re_h^{0.75} - 6.66) \cdot Pr_h^{0.42} \quad (20)$$

- Turbulent region ($Re_h \geq 8{,}000$):

$$Nu_h = 0.023 \cdot Re_h^{0.8} \cdot Pr_h^{0.33} \quad (21)$$

Step 22. Convective heat transfer coefficient for water (h_h):

$$h_h = \frac{Nu_h \cdot k_h}{d_h} \quad (22)$$

Step 23. Overall heat transfer coefficient (U):

$$U = \frac{1}{\frac{1}{h_{co}} + \frac{1}{h_h} + \frac{e_t}{k_t} + R_c + R_h} \quad (23)$$

Step 24. Log Mean Temperature Difference ($LMTD$):

- For a countercurrent arrangement:

$$LMTD = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\frac{(T_1 - t_2)}{(T_2 - t_1)}} \quad (24)$$

Step 25. Required heat exchange area (A_{req}):

$$A_{req} = \frac{Q}{U \cdot LMTD} \quad (25)$$

Step 26. Length of the heat exchanger (L):

$$L = \frac{A_{req}}{\pi \cdot n \cdot d_e} \quad (26)$$

2.3. Calculation of the pressure drops.

Step 27. Cross section area of tube-side nozzle ($a_{N(t)}$):

$$a_{N(t)} = \frac{\pi \cdot d_N^2}{4} \quad (27)$$

Step 28. Flow velocity of methanol in tube-side nozzle ($v_{N(c)}$):

$$v_{N(c)} = \frac{\frac{m_c}{3{,}600}}{\rho_c \cdot a_{N(t)}} \quad (28)$$

Step 29. Nozzle pressure drop of methanol in the tube side ($\Delta p_{N(c)}$):

$$\Delta p_{N(c)} = 1.5 \cdot \frac{v_{N(c)}^2 \cdot \rho_c}{2} \quad (29)$$

Step 30. Friction factor of methanol (f_c):

$$f_c = \frac{0.275}{Re_c^{0.2}} \quad (30)$$

Step 31. Frictional pressure drop of methanol in the tube side ($\Delta p_{f(c)}$):

$$\Delta p_{f(c)} = f_c \cdot \frac{L}{d_i} \cdot \frac{v_c^2 \cdot \rho_c}{2} \quad (31)$$

Step 32. Total pressure drop of methanol in the tube side (Δp_c):

$$\Delta p_c = \Delta p_{N(c)} + \Delta p_{f(c)} \quad (32)$$

Step 33. Cross section area of the shell-side nozzle ($a_{N(s)}$):

$$a_{N(s)} = \frac{\pi \cdot D_N^2}{4} \quad (33)$$

Step 34. Flow velocity of water in the shell-side nozzle ($v_{N(h)}$):

$$v_{N(h)} = \frac{\frac{m_h}{3{,}600}}{\rho_h \cdot a_{N(s)}} \quad (34)$$

Step 35. Nozzle pressure drop of water in the shell side ($\Delta p_{N(h)}$):

$$\Delta p_{N(h)} = 1.5 \cdot \frac{v_{N(h)}^2 \cdot \rho_h}{2} \quad (35)$$

Step 36. Hydraulic diameter for the pressure drop (d'_h):´

$$d'_h = \frac{D_i^2 - n \cdot d_e^2}{D_i + n \cdot d_e} \quad (36)$$

Step 37. Reynolds number of water for pressure drop (Re'_h):

$$Re'_h = \frac{d'_h \cdot v_h \cdot \rho_h}{\mu_h} \quad (37)$$

Step 38. Friction factor of water (f_h):

$$f_h = \frac{0.275}{Re'^{0.2}_h} \quad (38)$$

Step 39. Frictional pressure drop of water in the shell side ($\Delta p_{f(h)}$):

$$\Delta p_{f(h)} = f_h \cdot \frac{L}{d'_h} \cdot \frac{v_h^2 \cdot \rho_h}{2} \quad (39)$$

Step 40. Total pressure drop of water in the shell side (Δp_h):

$$\Delta p_h = \Delta p_{N(h)} + \Delta p_{f(h)} \quad (40)$$

3. Results.

The steps followed to determine the required tube length and the pressure drop of both streams, among other important parameters, are presented next, in order to design the multitube heat exchanger from the thermo-hydraulic point of view.

3.1. Tube length.

Step 1. Definition of the initial data available:

- Methanol mass flowrate (m_c): 2,000 kg/h.
- Water mass flowrate (m_h): 3,000 kg/h.
- Inlet temperature of methanol (t_1): 30 °C.
- Outlet temperature of methanol (t_2): 60 °C.
- Inlet temperature of water (T_1): 90 °C.
- Internal diameter of shell (D_i): 0.0721 m.
- Internal diameter of tubes (d_i): 0.014 m.
- External diameter of tubes (d_e): 0.016 m.
- Internal diameter of the tube side nozzle (d_N): 0.032 m.
- Internal diameter of the shell side nozzle (D_N): 0.050 m.
- Thermal conductivity of carbon steel (k_t): 43 W/m.K [11].
- Tube wall thickness (e_t): 0.002 m.
- Fouling factor of methanol (R_c): 0.000352 K.m^2/W [11].
- Fouling factor of water (R_c): 0.000088 K.m^2/W [11].
- Number of tubes (n): 7.
- Maximum allowable pressure drop for methanol [$\Delta P_{c(a)}$]: 3,500 Pa.
- Maximum allowable pressure drop for water [$\Delta P_{h(a)}$]: 1,000 Pa.

Step 2. Average temperature of methanol ($\bar{t}$):

$$\bar{t} = \frac{t_1 + t_2}{2} = \frac{30 + 60}{2} = 45\ ºC \quad (1)$$

Step 3. Physical parameters of methanol at the average temperature determined in step 1:

According to [13], the methanol has the values presented next for the requested physical parameters:

- Density (ρ_c) = 770.12 kg/m3.
- Viscosity (μ_c) = 0.000423 Pa.s.
- Heat capacity (Cp_c) = 2,657.53 J/kg.K.
- Thermal conductivity (k_c) = 0.1943 W/m.K.

Step 4. Heat duty (Q):

$$Q = \frac{m_c}{3{,}600} \cdot Cp_c \cdot (t_2 - t_1) \quad (2)$$

$$Q = \frac{2{,}000}{3{,}600} \cdot 2{,}657.53 \cdot (60 - 30)$$

$$Q = 44{,}292.17\ W$$

Step 5. Heat capacity of water (Cp_h) at the inlet water temperature (T_1).

As reported by [13], the heat capacity of water at 90 °C is 4,205.21 J/kg.K.

Step 6. Outlet temperature of water (T_2):

$$T_2 = T_1 - \frac{Q}{\frac{m_h}{3{,}600} \cdot Cp_h} \quad (3)$$

$$T_2 = 90 - \frac{44{,}292.17}{\frac{3{,}000}{3{,}600} \cdot 4{,}205.21}$$

$$T_2 = 77.36\ ºC$$

Step 7. Average temperature of water ($\bar{T}$):

$$\bar{T} = \frac{T_1 + T_2}{2} = \frac{90 + 77.36}{2} = 83.68\ ºC \quad (4)$$

Step 8. Physical parameters of water at the average temperature determined in step 6:

Consistent with [14], the water presents the values of the physical parameters presented next at the average temperature of 83.68 °C.

- Density (ρ_h) = 969.46 kg/m^3.
- Viscosity (μ_h) = 0.000339 Pa.s.
- Thermal conductivity (k_h) = 0.6721 W/m.K.

Table 1 presents the values of the parameters calculated in steps 9-26.

Table 1. Results of the parameters calculated in steps 9-26.

Step	Parameter	Symbol	Value	Units
9	Cross section area of tube	a_t	0.001077	m^2
10	Velocity of methanol on the tube-side	v_c	0.670	m/s
11	Reynolds number of methanol[1]	Re_c	17,077.36	-
12	Prandtl number of methanol	Pr_c	5.78	-
13	Nusselt number of methanol[2]	Nu_c	99.56	-
14	Convective heat transfer	h_c	1,381.75	W/m^2.K

	coefficient for methanol			
15	Convective heat transfer coefficient for methanol based on the tube outer surface area	h_{co}	1,209.03	W/m^2.K
16	Flow cross-section in the shell	a_{shell}	0.00267	m^2
17	Velocity of water on the shell	v_h	0.322	m/s
18	Hydraulic diameter for heat exchange	d_h	0.0304	m
19	Reynolds number of water[3]	Re_h	27,993.66	-
20	Prandtl number of water	Pr_h	2.12	-
21	Nusselt number of water[4]	Nu_h	106.43	-
22	Convective heat transfer coefficient for water	h_h	2,353.01	W/m^2.K
23	Overall heat transfer coefficient	U	575.17	W/m^2.K
24	Log Mean Temperature Difference	$LMTD$	38.02	ºC
25	Required heat exchange area	A_{req}	2.025	m^2
26	Length of the heat exchanger	L	5.76	m

[1] Since $Re_c > 8{,}000$, the methanol will flow under turbulent regime in the heat exchanger.
[2] Since $Re_c > 8{,}000$, the equation employed to determine the Nusselt number of methanol was number (11).
[3] Since $Re_h > 8{,}000$, the water will flow under turbulent regime in the heat exchanger.
[4] Since $Re_h > 8{,}000$, the equation (21) was employed to determine the Nusselt number of water.
Source: Own elaboration.

3.2. Pressure drops.

Table 2 shows the results of the parameters calculated in steps 27-40.

Table 2. Results of the parameters calculated in steps 27-40.

Step	Parameter	Symbol	Value	Units
27	Cross section area of the tube-side nozzle	$a_{N(t)}$	0.00080	m^2
28	Flow velocity of methanol in the tube-side nozzle	$v_{N(c)}$	0.902	m/s
29	Nozzle pressure drop of methanol in the tube side	$\Delta p_{N(c)}$	469.93	Pa
30	Friction factor of methanol	f_c	0.0392	-
31	Frictional pressure drop of methanol in the tube side	$\Delta p_{f(c)}$	2,787.73	Pa
32	Total pressure drop of methanol in the tube side	Δp_c	3,257.66	Pa
33	Cross section area of the shell-side nozzle	$a_{N(s)}$	0.00196	m^2
34	Flow velocity of water in the shell-side nozzle	$v_{N(h)}$	0.438	m/s
35	Nozzle pressure drop of water in the shell side	$\Delta p_{N(h)}$	139.49	Pa
36	Hydraulic diameter for the pressure drop	d'_h	0.0185	m
37	Reynolds number of water for pressure drop	Re'_h	17,035.61	-
38	Friction factor of water	f_h	0.0392	-
39	Frictional pressure drop of water in the shell side	$\Delta p_{f(h)}$	613.39	Pa
40	Total pressure drop of water in the shell side	Δp_h	752.88	Pa

Source: Own elaboration.

4. Discussion.

According to the results shown on Table 1, the velocity of methanol on the tube side was 0.670 m/s, which is 2.08 times higher than the velocity of water on the shell; this is due to the lowest value that the density of methanol (770.12 kg/m^3) and the cross section area of tube (0.001077 m^2) present with respect to the density of water (969.46 kg/m^3) and the flow cross-section in the shell (0.00267 m^2).

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The Reynolds number of water (27,993.66) is 1.64 times higher than the Reynolds number of methanol (17,077.36), which is due to the highest value that present the density of water (969.46 kg/m^3) and the hydraulic diameter for heat exchange (0.0304), and the lowest value of the viscosity of water (0.000339 Pa.s) with respect to the values of the density of methanol (770.12 kg/m^3), internal diameter of tube (0.014 m) and viscosity of methanol (0.000423 Pa.s). It's worth noting that both streams flow under turbulent regime since both Reynolds number are above 8,000 [10]. The convective heat transfer coefficient of water (2,353.01 W/m^2.K) is 1.70 times higher than the convective heat transfer coefficient for methanol (1,381.75 W/m^2.K) mostly because the Nusselt number (106.43) and the thermal conductivity (0.6721 W/m.K) of water are higher than the Nusselt number (99.56) and the thermal conductivity (0.1943 W/m.K) of methanol.

The heat duty was of 44,292.17 W, while the calculated outlet temperature of water was 77.36 ºC. The value of the overall heat transfer coefficient was 575.17 W/m^2.K, which agrees with the values reported by [4] and [11], while the Log Mean Temperature Difference was 38.02 ºC. The designed MTHE will need a heat exchange area of 2.025 m^2, which corresponds to the values reported by [4] for this type of heat exchanger, thus requiring a total length of 5.76 m, which can be considered adequate [3]. In [10], a MTHE was designed and the results of heat exchange area and the total tube length were 1.01 m^2 and 2.90 m, respectively.

The nozzle pressure drop of methanol in the tube side (469.93 Pa) is 3.37 times higher than nozzle pressure drop of water in the shell side (139.49 Pa) which is due to the fact that the value of the flow velocity of methanol in the tube-side nozzle (0.902 m/s) almost double the flow velocity of water in the shell-side nozzle (0.438 m/s). This occurred because the internal diameter of the tube side nozzle (0.032 m) is lower than the internal diameter of the shell side nozzle (0.050 m), thus resulting in a lower cross section area of the tube-side nozzle (0.00080 m^2) with respect to the cross section area of the shell-side nozzle (0.00196 m^2), therefore influencing in the higher value obtained for the flow velocity of methanol in the tube-side nozzle with respect to the value of the flow velocity of water in the shell-side nozzle. On the other hand, the frictional pressure drop of methanol in the tube side (2,787.73 Pa) is 4.54 times higher than the frictional pressure drop of water in the shell side (613.39 Pa), which is because the velocity of methanol on the tube-side (0.670 m/s) is higher and the internal diameter of tubes (0.014 m) is lower than the velocity of water on the shell (0.322 m) and the hydraulic diameter for the pressure drop (0.0185 m), respectively. It's worth mentioning that the value of the friction factor of methanol is equal to the value of the friction factor of water, that is, both have a value of 0.0392, which is an inquiring result.

The above discussion explains why the total pressure drop of methanol in the tube side (3,257.66 Pa) is 4.32 times higher than the total pressure drop of water in the shell side (752.88 Pa), that is, because both the nozzle pressure drop of methanol in the tube side and the frictional pressure drop of methanol in the tube side are higher in value than the nozzle pressure drop of water in the shell side and the frictional pressure drop of water in the shell side, respectively. This result agrees with that reported by [10].

Figure 2 displays the schematics of the designed MTHE, with its main design parameters and the numerical information of both streams.

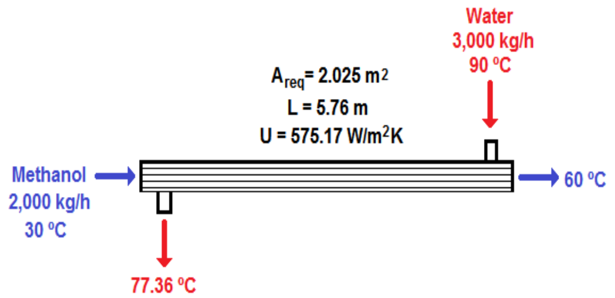

Fig. 2. Schematics of the designed MTHE.
Source: Own elaboration.

5. Conclusions.

A multi-tube heat exchanger was designed from the thermo-hydraulic point of view, in order to heat a methanol stream to 60 ºC using water condensate at 90 ºC. The calculation methodology employed in this study, in order to design the MTHE, was that reported by [10]. Several important design parameters were determined such as the Log Mean Temperature Difference (38.02 ºC), the overall heat transfer coefficient (575.17 W/m^2.K), the required heat exchange area (2.025 m^2), as well as the Reynolds, Prandtl and Nusselt numbers and the convective heat transfer coefficients for both fluids. The pressure drop of both streams were also calculated, whose values are below the maximum limits set by the heat exchange service. The designed multi-tube heat exchanger will present a total length of 5.76 m.

6.- Author Contributions.

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2. Data curation: Zamira María Sarduy Rodríguez.
3. Formal Analysis: Amaury Pérez Sánchez, Arlenis Cristina Alfaro Martínez.
4. Acquisition of funds: Not applicable.
5. Research: Amaury Pérez Sánchez, Arlenis Cristina Alfaro Martínez, Zamira María Sarduy Rodríguez.
6. Methodology: Amaury Pérez Sánchez, Elizabeth Ranero González.
7. Project management: Not applicable.
8. Resources: Not applicable.
9. Software: Not applicable.

10. Supervision: Amaury Pérez Sánchez.
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12. Visualization: Not applicable.
13. Writing – original draft: Elizabeth Ranero González, Eddy Javier Pérez Sánchez.
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Nomenclature

$a_{N(s)}$	Cross section area of the shell-side nozzle	m²
$a_{N(t)}$	Cross section area of the tube-side nozzle	m²
a_{shell}	Flow cross-section in the shell	m²
a_t	Cross section area of tube	m²
A_{req}	Required heat exchange area	m²
Cp	Heat capacity	J/kg.K
d_e	External diameter of tubes	m
d_h	Hydraulic diameter for heat exchange	m
d'_h	Hydraulic diameter for the pressure drop	m
d_i	Internal diameter of tubes	m
d_N	Internal diameter of the tube side nozzle	m
D_i	Internal diameter of shell	m
D_N	External diameter of the shell side nozzle	m
e_t	Tube wall thickness	m
f	Friction factor	-
h	Convective heat transfer coefficient	W/m².K
h_o	Convective heat transfer coefficient based on the tube outer surface area	
k	Thermal conductivity	W/m.K
k_t	Thermal conductivity of the tube material (carbon steel)	W/m.K
L	Length of the heat exchanger	
$LMTD$	Log Mean Temperature Difference	ºC
m	Mass flowrate	kg/h
n	Number of tubes	-
Nu	Nusselt number	-
Pr	Prandtl number	-
Δp	Total pressure drop	Pa
$\Delta P_{(a)}$	Maximum allowable pressure drop	Pa
$\Delta p_{f(c)}$	Frictional pressure drop of cold fluid in the tube side	Pa
$\Delta p_{f(h)}$	Frictional pressure drop of hot fluid in the shell side	Pa
$\Delta p_{N(c)}$	Nozzle pressure drop of cold fluid in the tube side	Pa
$\Delta p_{N(h)}$	Nozzle pressure drop of hot fluid in the shell side	Pa
Q	Heat duty	W
R	Fouling factor	K.m²/W
Re	Reynolds number	-
Re'	Reynolds number for pressure drop	
t	Temperature of the cold fluid	ºC
$\bar{t}$	Average temperature of the cold fluid	ºC
T	Temperature of the hot fluid	ºC
$\bar{T}$	Average temperature of the hot fluid	ºC

U	Overall heat transfer coefficient	$W/m^2.K$
v	Velocity	m/s
$v_{N(c)}$	Flow velocity of cold fluid in the tube-side nozzle	m/s
$v_{N(h)}$	Flow velocity of hot fluid in the shell-side nozzle	m/s

Greek symbols

ρ	Density	kg/m^3
μ	Viscosity	Pa.s

Subscripts

1	Inlet
2	Outlet
c	Cold fluid (methanol)
h	Hot fluid (water)

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Thermo-hydraulic design of a finned tube double-pipe heat exchanger for acetone cooling.

Diseño térmico-hidráulico de un intercambiador de calor de doble tubo aleteado para el enfriamiento de acetona.

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Abstract.
Finned tube double-pipe counter-flow heat exchangers are considered very effective, valuable and advantageous in the heat transfer industry. In the present paper a finned tube double pipe heat exchanger was designed applying a well-known design methodology, in order to cool down 2 kg/s of an acetone stream from 90 ºC to 30 ºC using chilled water available at 5 ºC. Several important design parameters were determined like the cleanliness factor and the number of hairpins, as well as the pressure drop and pumping power of both streams, among others. The heat load had a value of 276,030 W, while a mass flowrate of chilled water of 3.30 kg/s will be needed to cool the acetone stream. Both fluids will flow under turbulent regime inside the heat exchanger. The value of the cleanliness factor was 0.359, and about three hairpins will be needed. The pressure drop of both fluids are below the maximum value established by the heat exchange service, while the chilled water and acetone streams will need a pumping power of 3,662 W and 575 W, respectively.

Keywords.
Double pipe heat exchanger, finned tube, number of hairpins, pressure drop, pumping power.

Resumen.
Los intercambiadores de calor de flujo a de doble tubo aleteados a contracorriente son considerados muy efectivos, valiosos y ventajosos en la industria de la transferencia de calor. En el presente artículo un intercambiador de calor de doble tubo aleteado fue diseñado aplicando una metodología de diseño bien conocida, con el fin de enfriar 2 kg/s de una corriente de acetona desde 90 ºC hasta 30 ºC usando agua fría disponible a 5 ºC. Varios parámetros de diseño importantes fueron determinados tales como el factor de limpieza y el número de horquillas, así como también la caída de presión y potencia de bombeo de ambas corrientes, entre otros. La carga de calor tuvo un valor de 276 030 W, mientras que se necesitará un caudal másico de agua fría de 3,30 kg/s para enfriar la corriente de acetona. Ambos fluidos fluirán bajo régimen turbulento dentro del intercambiador de calor. El valor del factor de limpieza fue de 0,359, y se necesitarán alrededor de tres horquillas. La caída de presión de ambos fluidos está por debajo del valor máximo establecido por el servicio de transferencia de calor, mientras que las corrientes de agua fría y acetona necesitarán una potencia de bombeo de 3 662 W y 575 W, respectivamente.

Palabras clave.
Intercambiador de calor de doble tubo, tubo aleteado, número de horquillas, caída de presión, potencia de bombeo.

1. Introduction.

With the development of know-how, the significance of heat transfer engineering has boosted and there is a permanently need to encounter new design challenges to increase the performance and efficacy of the heat transfer field, particularly due to energy saving interests. Usually, heat exchangers are widely used for this purpose [1].

Heat exchangers are devices operated in numerous industries for heat transfer among fluids. Of the several types of heat exchangers that are utilized at industrial scale, possibly the two most significant are the double pipe and the shell and tube. Despite the fact that shell and tube heat exchangers generally provide greater surface area for heat transfer with a more compact design, greater ease of cleaning, and less probability of leakage, the double pipe heat exchanger (DPHE) still finds use in practice today [2].

One of the heat exchangers that have attracted the attention of researchers and engineers is the DPHE due to simplicity, effectiveness and wide range of usages [3].

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A DPHE is a distinctive type of heat exchanger with two concentric pipes, one inside the other. There are two different fluid flows in a DPHE, such that one fluid flows inside the inner pipe and the other fluid flows in the annulus region outside of the inner pipe [4]. It involves two concentric pipes, two connecting tees, a return head, a return feed, and packing glands that support the inner pipe within the outer pipe (Figure 1). Each of two fluids −hot and cold− flow either through the inside of the inner pipe or through the annulus formed between the outside of the inner pipe and the inside of the outer pipe [2].

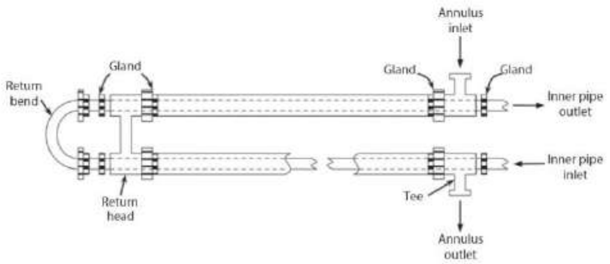

Fig. 1. Double pipe heat exchanger.
Source: [2].

DPHE have been utilized in the chemical processing industry for over 100 years. The first patent on this unit appeared in 1923 [2]. They are applied in several industrial processes and research areas; for example in waste heat recovery, for heating/cooling in chemical processes, as well as in the food industry to pasteurize/preheat liquid products (juices, mashes, jelly, etc.).

The DPHE is particularly convenient because it can be connected in any pipe-fitting shop from standard parts and offers an economical heat-transfer surface. The flow arrangement in this heat exchanger could be countercurrent or parallel (co-current). In countercurrent arrangement, the fluid in the pipe flows in a direction reverse to the fluid in the annulus. In parallel arrangement, the two fluids flow in the same direction. The variations of fluid temperature within the heat exchanger depend on whether the flow is parallel or countercurrent [2].

The main application of the DPHE is for sensible heating or cooling of process fluids where small heat transfer areas (up to 50 m^2) are necessary. This heat exchanger is also very appropriate for handling fluids with high pressure, because of the smaller diameter of the pipes. The major disadvantage is that they are bulky and expensive per unit of heat transfer surface area [5].

Although this unit is not extensively employed in industry (the heat transfer area is small relative to other heat exchangers), it serves as an excellent starting point from an academic and/or training perspective [2].

According to [6], if the stream contains solids in suspension, DPHEs may also be a better alternative, because they can be built with an inner tube with larger diameter to avoid plugging. Smaller diameters of the outer tube in DPHEs are effective for high-pressure applications, because it involves a smaller wall thickness. In addition, DPHEs may be easily cleaned, and the longitudinal flow avoids the existence of stagnation regions, which in shell and tube exchangers may cause fouling and corrosion. DPHEs have also the advantage of robustness due to its modular structure, which permits an easier adaptation to process adjustments.

Growing need to develop and improve the effectiveness of heat exchangers has led to a broad range of investigations for increasing heat transfer rate along with decreasing the size and cost of the industrial apparatus accordingly [3]. The enhancement of heat transfer has become an important factor in achieving these goals and has captured the interest of many researchers [7].

Enhancement of heat transfer in heat exchangers can be accomplished through two techniques [7]:
1. Increasing the convection coefficient. The convection coefficient may be improved by increasing turbulence, creating secondary flow, and inducing swirl flow. One or more of these mechanisms may be accomplished using coil-spring wire, ribs, indentation, spiral flutes transverse-ribbed tubes, helically ribbed tubes, wire-coil insert, twisted-tape insert, ribbed or ribbed grooved walls. Also, the convective heat transfer coefficient may be enhanced using fluids that experience a phase transition or by using electrohydrodynamic enhancement tools and employing mist flow.
2. Expanding the heat transfer area by employing longitudinal fins, wire-on-tube heat exchangers.
Other techniques apply both effects. Examples of these techniques are spiral fins or ribs and offset strip fins.

According to [4] the performance of heat exchangers can be enhanced by adopting appropriate procedures. These procedures comprise the implementation of extended surfaces, surface vibration, rough surfaces, and coiled tubes. Other authors [7] numerically investigated the effect of inserting porous substrates at both sides of the wall that separates the cold and hot working fluids on the performance of a conventional concentric tube heat exchanger.

Thermal systems are currently amongst the most dynamic technical systems. Numerous methods have been explored and tested in order to increase heat transfer in these systems and accomplish a high level of thermal performance. By exploiting a number of surface-enhancement-based approaches, the heat transfer rate of conventional heat exchangers may be improved. This development in heat transfer rate results from the conditions provided by the use of enhanced surfaces. These conditions prevent the formation of the boundary layer, improve the turbulence level, increase the heat transfer area, and generate swirling and/or secondary flows. Enhanced heat transfer surfaces have several objectives for their use, being the most important to reduce the size of heat exchangers, which could lead to a decrease in their costs. In addition, they reduce the pumping power that is needed for specific thermal exchange processes, and improve the heat transfer coefficient. In turn, this increases the effectiveness and efficiency of thermal processes and results in operating cost savings [8].

Recently, several researchers have investigated ways to enhance heat transfer using the passive way in double-pipe heat exchangers (DPHE), such as using twisted strips, extended surfaces or fins, wired coils, and other turbulence-generating tools [9].

The use of solid fins to boost the heat transfer rates between two different fluids in tubular heat exchangers is one of the most successful and extensively applied approaches. Finned tubes are one of the most commonly used ways of passively enhancing the heat transfer in circular tube. They are applied to decrease the size of a heat exchanger required for a specified heat duty, or to increase heat transfer rate of an existing heat exchanger design. An internally finned tube can substantially increase the surface area, and can significantly augment the heat transfer rate. Finned tubes perform differently depending on whether the flow is laminar or turbulent. For both laminar and turbulent flow regimes, the finned tubes exhibit significantly higher heat transfer coefficients when contrasted with the corresponding smooth tubes. The performance of finned pipe is mainly determined by the type of flow, fin efficiency (which determines the average heat transfer coefficient) and the friction factor, which is responsible for pressure/pumping loss [10].

The use of a finned tube to increase heat transmission is becoming more important in a growing number of industrial applications; thus, the finned tube has been the subject of several studies [8]. In this context, [9] investigated the convection heat transfer in a countercurrent double-tube heat exchanger with a curved rectangular fin and rectangular fin in a turbulent flow using water-Al_2O_3 and water-TiO_2 nanofluids. Also, in [11] the enhancement of the thermal performance of the phase change material in a double-tube heat exchanger using new grid annular fins was investigated. In this study, the grid annular fins, which consisted of straight and circular strip components, were located on the inner tube. In another study, [8] carried out a numerical investigation of heat transfer enhancement in a double pipe heat exchanger embedded with an extended surface on the inner tube's outer surface with the addition of Alumina nanofluid and by using computational fluid dynamics (CFD) simulation. This investigation was carried out at Reynolds numbers ranging from 250 to 2,500 with an inner diameter of 20.4 mm. while the effect of the inner pipe's U fins' geometry on pressure drop, temperature distribution, and thermal performance was also scrutinized. Moreover, [12] carried out the numerical examination of heat transfer enhancement in individual annular serrated fins double tube heat exchanger, concluding that the maximum value of Nusselt number and maximal skin friction coefficient was found in 14 serrated fins. Besides, [4] studied the characteristics of convective heat transfer in the annular region of a finned DPHE with an innovative diamond-shaped fin design. The diamond-shaped fins are longitudinally increased on the outer surface of the inner pipe of the DPHE. The arrangement of the diamond-finned annulus was verified by the numerous values of the geometrical parameters, such as the radii ratio, fins number, fin-height, and fin thickness. The effects of these variables on various performance parameters, such as the product of the Reynolds number and friction factor, Nusselt number, and j-factor, were computed. The type of fin evaluated in this study was considered for the first time in the design of DPHEs. In [10] a simple semi-empirical-numerical methodology to evaluate heat transfer and pressure drop characteristics in a finned tube heat exchanger with internal and/or external fins was described, which can be applied in a wide range of operating conditions of practical importance. In [3] the thermo hydraulic performance of a proposed design of an air-to-water double pipe heat exchanger with helical fins on the annulus gas side was numerically studied. Three-dimensional CFD simulations were implemented, using the FLUENT software with the aim of examine the gas side fluid flow, turbulence, heat transfer, and power consumption for different arrangements of the heat exchanger. Moreover, [13] carried out various experiments to investigate and compare the heat transfer in a DPHE for counter flow arrangement with and without usage of longitudinal triangular fins. Triangular fins with dimensions of 9 mm base, 8 mm height and 2 mm thickness were applied in this study. Other authors [6] investigated the design optimization of a DPHE using mathematical programming. The heat exchanger area is decreased and the thermo-fluid dynamic settings are considered for the application of the right transport equations, together with design conditions, such as maximum pressure drops and minimum excess area. The modular structure of this heat exchanger type and the allocation of the streams (inside the inner tube or in the annulus) are also considered. Two mixed-integer nonlinear programming (MINLP) approaches were also purported. Likewise, [14] aimed to develop new designs of DPHE to improve the heating/cooling processes at the lowest possible pumping power. Consequently, the thermal performance analysis of three configurations of DPHE was implemented. The studied arrangements were circular wavy DPHE, plain oval DPHE and an oval wavy DPHE. In addition, the conventional DPHE was utilized as a reference heat exchanger, and a validated CFD approach was executed to perform this study. In [15], the helical fins effect in the performance of a water-air DPHE was examined experimentally. The performance in terms of average heat transfer rate, heat transfer coefficient and effectiveness of heat exchanger in plain inner pipe (without helical fin) was assessed and contrasted with a heat exchanger having helical fins installed over inner pipe. In [1], the analysis of fully developed laminar convective heat transfer in an innovated design of a finned DPHE with longitudinal fins of variable thickness of the tip subjected to the constant heat transfer rate boundary conditions was investigated. In this study, the overall performance of the proposed DPHE was examined by taking into account the friction factor, the Nusselt number and the j-factor. Finally, [16] aimed at comparison of heat transfer characteristics using different fin profiles for a DPHE under various operating conditions to evolve with the best possible configuration. The selected configurations in this study were rectangular, triangular and concave parabolic. Base width, height and number of fins were held identical to be specifically compared. Numerical simulation was completed using commercial CFD software. Several particular heat transfer parameters like temperature deviation, heat transfer rate, heat transfer coefficient and fin effectiveness for the models mentioned above were compared and shown.

The addition of porous material as an alternative method to improve heat exchange in these thermal equipment seems to be promising. In this sense, [17] investigated the heat transfer enhancement when porous fins are attached at the inner cylinder of a DPHE. This arrangement is selected in order to augment the heat transfer surface area between the fins and the cold fluid to be heated. The influence of several parameters such as Darcy number, the height and spacing of fins and the thermal conductivity ratio on the hydrodynamic and thermal fields were also investigated.

Liquid acetone is produced in a chemical processing plant, and it's desired to cool down this liquid acetone stream from 90 ºC to 30 ºC, using chilled water available at 5 ºC. To accomplish this heat exchange operation, a finned tube double pipe heat exchanger has been proposed due to space availability and limited budget. Thus, the present paper aimed to design a finned tube DPHE both from the thermal and hydraulic points of view, using the methodology and correlations reported in [5] and [18], where several important design parameters were determined such as the cleanliness factor and the total number of hairpins, as well as the pressure drop and pumping power of both streams.

2. Materials and methods.

2.1. Problem definition.

It's required to cool 2 kg/s of an acetone stream from 90 ºC to 30 ºC using chilled water at 5 ºC. The chilled water outlet temperature must not be higher than 25 ºC. The following initial parameters are available (Figure 2):

- Length of hairpin (L_t): 4.2 m.
- Nominal diameter of annulus: 2 in.
- Nominal diameter of inner tube: ¾ in.
- Fin height (H_f): 0.0125 m
- Fin thickness (δ): 0.9 mm.
- Number of fins per tube (N_f): 28.
- Material: Carbon steel.
- Thermal conductivity of carbon steel (k_m): 52 W/m.K [5].
- Number of tubes inside the annulus (N_t): 1.

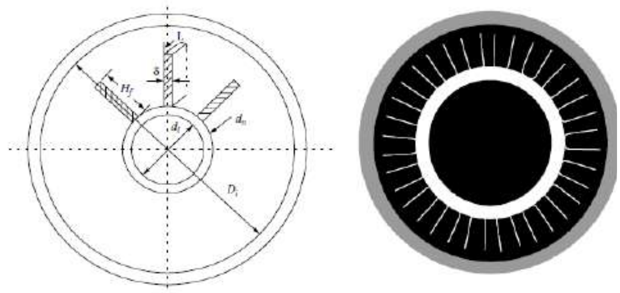

Fig. 2. Cross section of a longitudinally finned inner tube heat exchanger and nomenclature of the initial parameters.
Source: [5].

According to [5] the fouling factors for acetone and water are 0.000352 and 0.000176 m^2.K/W respectively. It's preferred that both streams flow under countercurrent arrangement in the designed heat exchanger, while the pressure drop of the acetone and chilled water must not exceed 200,000 Pa and 900,000 Pa, respectively. Calculate the surface area and the number of hairpins of the heat exchanger, as well as the pressure drops and pumping power for both streams.

2.2. Number of hairpins.

Step 1. Definition of the initial parameters.
Step 2. Diameters of both the inner tube and annulus.
Step 3. Average temperature of both fluids:

- Hot fluid:

$$\overline{T} = \frac{T_1 + T_2}{2} \quad (1)$$

- Cold fluid:

$$\overline{t} = \frac{t_1 + t_2}{2} \quad (2)$$

Step 4. Physical properties of both fluids at the average temperature of the previous step.
Table 1 shows the physical properties that must be defined for both fluids at the average temperature calculated in the previous step.

Table 1. Physical properties of both fluids

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Physical property	Acetone	Chilled water	Units
Density	ρ_h	ρ_c	kg/m³
Viscosity	μ_h	μ_c	Pa.s
Thermal conductivity	k_h	k_c	W/m.K
Heat capacity	Cp_h	Cp_c	J/kg.K

Source: Own elaboration.

Step 5. Heat load (Q):

$$Q = m_h \cdot Cp_h \cdot (T_1 - T_2) \tag{3}$$

Step 6. Mass flowrate of chilled water (m_c):

$$m_c = \frac{Q}{Cp_c \cdot (t_2 - t_1)} \tag{4}$$

Step 7. Location of the fluids inside the heat exchanger.

Step 8. Net cross-sectional area in the annulus with longitudinal finned tubes (A_c):

$$A_c = \frac{\pi}{4} \cdot (D_i^2 - d_o^2 \cdot N_t) - \delta \cdot H_f \cdot N_t \cdot N_f \tag{5}$$

Step 9. Total wetted perimeter of the annulus with longitudinally finned inner tubes (P_w):

$$P_w = \pi \cdot (D_i + d_o \cdot N_t) + 2 \cdot H_f \cdot N_f \cdot N_t \tag{6}$$

Step 10. Hydraulic diameter (D_h):

$$D_h = \frac{4 \cdot A_c}{P_w} \tag{7}$$

Step 11. Heat transfer perimeter of the annulus for heat transfer (P_h):

$$P_h = \left(\pi \cdot d_o + 2 \cdot H_f \cdot N_f\right) \cdot N_t \tag{8}$$

Step 12. Equivalent diameter for heat transfer (D_e):

$$D_e = \frac{4 \cdot A_c}{P_h} \tag{9}$$

Step 13. Velocity of the tube side fluid (u_t):

$$u_t = \frac{m_t}{\rho_t \cdot \frac{\pi \cdot d_i^2}{4}} \tag{10}$$

Step 14. Reynolds number of the tube side fluid (Re_t):

$$Re_t = \frac{\rho_t \cdot u_t \cdot d_i}{\mu_t} \tag{11}$$

Step 15. Prandtl number of the tube side fluid (Pr_t):

$$Pr_t = \frac{Cp_t \cdot \mu_t}{k_t} \tag{12}$$

Step 16. Nusselt number of the tube side fluid (Nu_t):

- Laminar regime (Re_t < 2,300):

Temperature of the tube wall (T_w):

$$T_w = 0.5 \cdot (\bar{T} - \bar{t}) \tag{13}$$

Viscosity of the tube side fluid (μ_t) and water (μ_w) at T_w.
Nusselt number of the tube side fluid under laminar flow:

$$Nu_t = 1.86 \cdot \left(Re_t \cdot Pr_t \cdot \frac{d_i}{L_t}\right)^{1/3} \cdot \left(\frac{\mu_t}{\mu_w}\right)^{0.14} \tag{14}$$

- Transition regime (2,300 ≤ Re_t ≤ 10,000):

$$\frac{h_t}{Cp_t \cdot \rho_t \cdot u_t} = 0.116 \cdot \left(\frac{Re_t^{0.66} - 125}{Re_t}\right) \cdot \left[1 + \left(\frac{d_i}{L_t}\right)^{0.66}\right] \cdot Pr_t^{-0.66} \cdot \tag{15}$$

- Turbulent regime (10,000 < Re_t < 5,000,000):

Friction factor (f_t):

$$f_t = (1.58 \cdot \ln Re_t - 3.28)^{-2} \tag{16}$$

Nusselt number (Nu_t):

$$Nu_t = \frac{\left(\frac{f_t}{2}\right) \cdot Re_t \cdot Pr_t}{1.07 + 12.7 \cdot \left(\frac{f_t}{2}\right)^{1/2} \cdot \left(Pr_t^{2/3} - 1\right)} \tag{17}$$

Step 17. Convective heat transfer coefficient of the tube side fluid (h_t):

$$h_t = \frac{Nu_t \cdot k_t}{d_i} \tag{18}$$

Step 18. Velocity of the annulus fluid (u_a):

$$u_a = \frac{m_a}{\rho_a \cdot A_c} \tag{19}$$

Step 19. Reynolds number of the annulus fluid (Re_a):

$$Re_a = \frac{\rho_a \cdot \mu_a \cdot D_h}{\mu_a} \tag{20}$$

Step 20. Prandtl number of the annulus fluid (Pr_a):

$$Pr_a = \frac{Cp_a \cdot \mu_a}{k_a} \tag{21}$$

Step 21. Nusselt number of the annulus fluid (Nu_a):

- Laminar regime (Re_a < 2,300):

Viscosity of the annulus fluid (μ_a) at T_w.
Nusselt number of the annulus fluid:

$$Nu_a = 1.86 \cdot \left(Re_a \cdot Pr_a \cdot \frac{D_h}{L_t}\right)^{1/3} \cdot \left(\frac{\mu_a}{\mu_w}\right)^{0.14} \tag{22}$$

- Transition regime (2,300 ≤ Re_a ≤ 10,000):

$$\frac{h_t}{Cp_a \cdot \rho_a \cdot u_a} = 0.116 \cdot \left(\frac{Re_a^{0.66} - 125}{Re_a}\right) \cdot \left[1 + \left(\frac{D_h}{L_t}\right)^{0.66}\right] \cdot Pr_a^{-0.6} \tag{23}$$

- Turbulent regime (10,000 < Re_a < 5,000,000):

Friction factor (f_a):

$$f_a = (1.58 \cdot lnRe_a - 3.28)^{-2} \quad (24)$$

Nusselt number (Nu_a):

$$Nu_t = \frac{\left(\frac{f_a}{2}\right) \cdot Re_a \cdot Pr_a}{1.07 + 12.7 \cdot \left(\frac{f_a}{2}\right)^{1/2} \cdot \left(Pr_a^{2/3} - 1\right)} \quad (25)$$

Step 22. Convective heat transfer coefficient of the annulus fluid (h_a):

$$h_a = \frac{Nu_a \cdot k_a}{D_e} \quad (26)$$

Step 23. Finned heat transfer area (A_f):

$$A_f = 2 \cdot N_t \cdot N_f \cdot L_t \cdot \left(2 \cdot H_f + \delta\right) \quad (27)$$

Step 24. Unfinned heat transfer area (A_u):

$$A_u = 2 \cdot N_t \cdot \left(\pi \cdot d_o \cdot L_t - N_f \cdot L_t \cdot \delta\right) \quad (28)$$

Step 25. Total area of hairpin (A_t):

$$A_t = A_f + A_u \quad (29)$$

Step 26. Factor m:

$$\mathrm{m} = \sqrt{\frac{2 \cdot h_a}{\delta \cdot k_m}} \quad (30)$$

Step 27. Fin efficiency (η_f):

$$\eta_f = \frac{tanh\left(m \cdot H_f\right)}{m \cdot H_f} \quad (31)$$

Step 28. Overall surface efficiency (η_o):

$$\eta_o = \left[1 - \left(1 - \eta_f\right) \cdot \frac{A_f}{A_t}\right] \quad (32)$$

Step 29. Area of the inner tube (A_i):

$$A_i = 2 \cdot \pi \cdot d_i \cdot L_t \quad (33)$$

Step 30. Overall heat transfer coefficient under fouled conditions (U_f):

$$U_f = \frac{1}{\frac{A_t}{A_i} \cdot \frac{1}{h_t} + \frac{A_t}{A_i} \cdot R_t + \frac{A_t \cdot ln\left(\frac{d_o}{d_i}\right)}{2 \cdot \pi \cdot k_m \cdot 2 \cdot L_t} + \frac{R_a}{\eta_o} + \frac{1}{\eta_o . h}} \quad (34)$$

Step 31. Overall heat transfer coefficient under clean conditions (U_c):

$$U_c = \frac{1}{\frac{A_t}{A_i} \cdot \frac{1}{h_t} + \frac{A_t \cdot ln\left(\frac{d_o}{d_i}\right)}{2 \cdot \pi \cdot k_m \cdot 2 \cdot L_t} + \frac{1}{\eta_o . h_a}} \quad (35)$$

Step 32. Cleanliness factor (CF):

$$\mathrm{CF} = \frac{U_f}{U_c} \quad (36)$$

Step 33. Log-mean temperature difference (LMTD) (for countercurrent flow):

$$\mathrm{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\frac{(T_1 - t_2)}{(T_2 - t_1)}} \quad (37)$$

Step 34. Total heat transfer surface area without fouling (A_{oc}):

$$A_{oc} = \frac{Q}{U_c \cdot LMTD} \quad (38)$$

Step 35. Total heat transfer surface area with fouling (A_{of}):

$$A_{of} = \frac{Q}{U_f \cdot LMTD} \quad (39)$$

Step 36. Number of hairpins (N_h):

$$N_h = \frac{A_{of}}{A_t} \quad (40)$$

2.3. Pressure drop.

Step 37. Friction factor of the tube side fluid (f_t'):

- Laminar regime (Re_t < 2,300):

$$f_t = \frac{16}{Re_t} \quad (41)$$

Friction factor of the tube side fluid under laminar flow:

$$f_t' = f_t \cdot \left(\frac{\mu_t}{\mu_w}\right)^{-0.58} \quad (42)$$

- Turbulent regime (4,000 < Re_t < 5,000,000):

$$f_t' = 0.00140 + 0.125 \cdot Re_t^{-0.32} \quad (43)$$

Step 38. Pressure drop of the tube side fluid (Δp_t):

$$\Delta p_t = 4 \cdot f_t' \cdot \frac{2 \cdot L_t}{d_i} \cdot \rho_t \cdot \frac{u_t^2}{2} \cdot N_h \quad (44)$$

Step 39. Friction factor of the annulus fluid (f_a'):

- Laminar regime (Re_a < 2,300):

$$f_a = \frac{16}{Re_a} \quad (45)$$

Friction factor of the annulus fluid under laminar flow:

$$f_a' = f_a \cdot \left(\frac{\mu_a}{\mu_w}\right)^{-0.58} \quad (46)$$

- Turbulent regime (4,000 < Re_a < 5,000,000):

$$f_a' = 0.00140 + 0.125 \cdot Re_a^{-0.32} \quad (47)$$

Step 40. Pressure drop of the annulus fluid (Δp_a):

$$\Delta p_a = 4 \cdot f_a' \cdot \frac{2 \cdot L_t}{D_h} \cdot \rho_a \cdot \frac{u_a^2}{2} \cdot N_h \quad (48)$$

2.4. Pumping power.

Step 41. Pumping power required for the tube side fluid (P_t):

$$P_t = \frac{m_t \cdot \Delta p_t}{\rho_t \cdot \eta_p} \quad (49)$$

Where η_p is the pump efficiency = 0.80 - 0.85 [5].

Step 42. Pumping power required for the annulus fluid (P_a):

$$P_a = \frac{m_a \cdot \Delta p_a}{\rho_a \cdot \eta_p} \quad (50)$$

3. Results.

The values of the main design parameters calculated for the proposed finned tube double-pipe heat exchanger are shown hereafter, which include the calculated number of hairpins, as well as the pressure drop and pumping power for both streams.

3.1. Number of hairpins.

Step 1. Definition of the initial parameters:
Table 2 shows the initial parameters which are required to design the double-pipe heat exchanger.

Table 2. Initial parameters available.

Parameters	Symbol	Value	Units
Mass flowrate of acetone	m_h	2.00	kg/s
Inlet temperature of acetone	T_1	90	ºC
Outlet temperature of acetone	T_2	30	ºC
Inlet temperature of water	t_1	5	ºC
Outlet temperature of water	t_2	25	ºC
Fouling factor of acetone	R_h	0.000352	m^2.K/W
Fouling factor of water	R_c	0.000176	m^2.K/W
Maximum pressure drop for acetone	Δp_{hm}	200,000	Pa
Maximum pressure drop for water	Δp_{cm}	900,000	Pa

Source: Own elaboration.

Step 2. Diameters of both the inner tube and annulus.
Presented next are the values of the inner and outer diameters for an inner tube with a nominal diameter of ¾ Schedule 40, and also the outer diameter for an annulus with a nominal diameter 2 Schedule 40, as reported by [19].

- Inner diameter of tube (d_i) = 0.02093 m.
- Outer diameter of tube (d_o) = 0.02667 m.
- Inner diameter of annulus (D_i) = 0.0525 m.

Step 3. Average temperature of both fluids:

- Acetone:

$$\bar{T} = \frac{T_1 + T_2}{2} = \frac{90 + 30}{2} = 60 \text{ °C} \quad (1)$$

- Water:

$$\bar{t} = \frac{t_1 + t_2}{2} = \frac{5 + 25}{2} = 15 \text{ °C} \quad (2)$$

Step 4. Physical properties of both fluids at the average temperature of the previous step.
Table 3 displays the values of the physical properties for both fluids, which were determined according to data reported in [19].

Table 3. Physical properties of both fluids.

Physical property	Acetone	Chilled water	Units
Density	745.20	999.10	kg/m^3
Viscosity	0.000229	0.00114	Pa.s
Thermal conductivity	0.146	0.589	W/m.K
Heat capacity	2,300.25	4,188.47	J/kg.K

Source: Own elaboration.

Step 5. Heat load (Q):

$$Q = m_h \cdot Cp_h \cdot (T_1 - T_2) \quad (3)$$

$$Q = 2.00 \cdot 2{,}300 \cdot (90 - 30) = 276{,}030\ W$$

Step 6. Mass flowrate of chilled water (m_c):

$$m_c = \frac{Q}{Cp_c \cdot (t_2 - t_1)} \quad (4)$$

$$m_c = \frac{276{,}030}{4{,}188.47 \cdot (25 - 5)} = 3.30\ kg/s$$

Step 7. Location of the fluids inside the heat exchanger:
According to suggestions stated by [2] and [20], the cold fluid (water) will be located inside of the inner tube, while the hot fluid (acetone) will flow on the annulus. Thus, the Table 4 presents the former and new symbols that will present the initial parameters for both fluids, taking into account the selected location of fluids. That is the subscripts h and c will be replaced by a and t, respectively, for all the initial parameters and physical properties of both fluids.

Table 4. Former and new symbols of the initial parameters for both fluids.

Parameter	Former symbol	New symbol	Units
Mass flowrate of acetone	m_h	m_a	kg/s
Mass flowrate of water	m_c	m_t	kg/s

Density of acetone	ρ_h	ρ_a	kg/m^3
Density of water	ρ_c	ρ_t	kg/m^3
Viscosity of acetone	μ_h	μ_a	Pa.s
Viscosity of water	μ_c	μ_t	Pa.s
Thermal conductivity of acetone	k_h	k_a	W/m.K
Thermal conductivity of water	k_c	k_t	W/m.K
Heat capacity of acetone	Cp_h	Cp_a	J/kg.K
Heat capacity of water	Cp_c	Cp_t	J/kg.K
Fouling factors of acetone	R_h	R_a	m^2.K/W
Fouling factors of water	R_c	R_t	m^2.K/W

Source: Own elaboration.

Table 5 exhibits the results of the parameters determined in steps 8 to 17.

Table 5. Results of the parameters determined in steps 8 – 17.

Step	Parameter	Symbol	Value	Units	Equat.
8	Net cross-sectional area in the annulus with longitudinal finned tubes	A_c	0.00129	m^2	(5)
9	Total wetted perimeter of the annulus with longitudinally finned inner tubes	P_w	0.949	m	(6)
10	Hydraulic diameter	D_h	0.0054	m	(7)
11	Heat transfer perimeter of the annulus for heat transfer	P_h	0.784	m	(8)
12	Equivalent diameter for heat transfer	D_e	0.0066	m	(9)
13	Velocity of the water	u_t	9.60	m/s	(10)
14	Reynolds number of the water[1]	Re_t	176,094	-	(11)
15	Prandtl number of the water	Pr_t	8.10	-	(12)
	Friction factor	f_t	0.0040	-	(16)
16	Nusselt number of the water	Nu_t	1,017.61	-	(17)
17	Convective heat transfer coefficient of the water	h_t	28,637	W/m^2.K	(18)

[1]Since Re_t > 10,000 the tube-side fluid flows under turbulent regime, thus equations (16) and (17) will be used to determine the Nusselt number.
Source: Own elaboration.

Table 6 exhibits the results of the parameters calculated in steps 18 to 22.

Table 6. Results of the parameters determined in steps 18 – 22.

Step	Parameter	Symbol	Value	Units	Equat.
18	Velocity of the acetone	u_a	2.08	m/s	(19)
19	Reynolds number of the acetone[1]	Re_a	36,550.6	-	(20)
20	Prandtl number of the acetone	Pr_a	3.61	-	(21)
	Friction factor	f_a	0.0056	-	(24)
21	Nusselt number of the acetone	Nu_a	186.69	-	(25)
22	Convective heat transfer coefficient of the acetone	h_a	4,127.6	W/m^2.K	(26)

[1]Since Re_a > 10,000 the annulus fluid flows under turbulent regime, thus equations (24) and (25) will be used to determine the Nusselt number.
Source: Own elaboration.

Table 7 shows the results of the parameters calculated in steps 23 to 36.

Table 7. Results of the parameters determined in steps 23 – 36.

Step	Parameter	Symbol	Value	Units	Equat.
23	Finned heat transfer area	A_f	6.092	m^2	(27)
24	Unfinned heat transfer area	A_u	0.492	m^2	(28)
25	Total area of hairpin	A_t	6.584	m^2	(29)
26	Factor	m	420	-	(30)
27	Fin efficiency	η_f	0.190	-	(31)
28	Overall surface efficiency	η_o	0.250	-	(32)
29	Area of the inner tube	A_i	0.552	m^2	(33)
30	Overall heat transfer coefficient (fouled)	U_f	182.65	W/m^2.K	(34)

31	Overall heat transfer coefficient (clean)	U_c	508.39	W/m^2.K	(35)
32	Cleanliness factor	CF	0.359	-	(36)
33	Log-mean temperature difference	$LMTD$	41.86	ºC	(37)
34	Total heat transfer surface area without fouling	A_{oc}	12.97	m^2	(38)
35	Total heat transfer surface area with fouling	A_{of}	36.10	m^2	(39)
36	Number of hairpins	N_h	2.78 ≈ 3	-	(40)

Source: Own elaboration.

3.2. Pressure drop.
Since the tube side fluid (water) flows under turbulent regime (Re_t = 176,094 > 10,000), the equations (43) and (44) were used to determine the pressure drop for this fluid. Accordingly:

Step 37. Friction factor of water (f_t') for turbulent regime:

$$f_t' = 0.00140 + 0.125 \cdot Re_t^{-0.32} = 0.0040 \quad (43)$$

Step 38. Pressure drop of water (Δp_t):

$$\Delta p_t = 4 \cdot f_t' \cdot \frac{2 \cdot L_t}{d_i} \cdot \rho_t \cdot \frac{u_t^2}{2} \cdot N_h = 886{,}903\ Pa \quad (44)$$

Because the annulus fluid (acetone) flows under turbulent regime (Re_a = 36,550.6 > 10,000), the equations (47) and (48) were used to determine the pressure drop for this fluid. Therefore:
Step 39. Friction factor of acetone (f_a') for turbulent regime:

$$f_a' = 0.00140 + 0.125 \cdot Re_a^{-0.32} = 0.0057 \quad (47)$$

Step 40. Pressure drop of acetone (Δp_a):

$$\Delta p_a = 4 \cdot f_a' \cdot \frac{2 \cdot L_t}{D_h} \cdot \rho_a \cdot \frac{u_a^2}{2} \cdot N_h = 171{,}518\ Pa \quad (48)$$

3.3. Pumping power.
Step 41. Pumping power required for the water (P_t):

$$P_t = \frac{m_t \cdot \Delta p_t}{\rho_t \cdot \eta_p} = 3{,}662\ W \quad (49)$$

Step 42. Pumping power required for the acetone (P_a):

$$P_a = \frac{m_a \cdot \Delta p_a}{\rho_a \cdot \eta_p} = 575\ W \quad (50)$$

4. Discussion.
The heat load necessary to cool down the acetone stream was of 276,030 W, while a mass flowrate of chilled water of 3.30 kg/s is needed by the heat exchange process. The velocity of chilled water (9.60 m/s) is 4.61 times higher than the velocity of acetone (2.08 m/s). This is because the higher value of the chilled water mass flowrate (3.30 kg/s) as compared to the mass flowrate of acetone (2.0 kg/s), as well as to the higher value of the parameter net cross-sectional area in the annulus with longitudinal finned tubes (0.00129 m^2) used in equation (19), as compared with the value of the term $\pi \cdot d_i / 4$ (0.00034 m^2) used in equation (10).

The Reynolds number of the chilled water (176,094) is about 4.82 times higher than the Reynolds number of acetone (36,550.6), which is due to the higher value of the velocity (9.60 m/s) and density (999.10 kg/m^3) of the chilled water compared to the values of these parameters for the acetone (velocity of 2.08 m/s and density of 745.20 kg/m^3). Also, the higher value obtained for the inner diameter of the tube (0.02093 m), as compared to the value of the hydraulic diameter (0.0054 m), influenced in this result. As stated above, the fluids will flow under turbulent regime inside the designed DPHE since the calculated values of the Reynolds number for both fluids are higher than 10,000.

In case of the Nusselt number, the value of this parameter for chilled water (1,017.61) is 5.45 times higher than the Nusselt number of acetone (186.69), which is due to the higher values obtained of Reynolds (176,094) and Prandtl (8.10) number for chilled water as compared to the values of this parameters for acetone (Reynolds number of 36,550.6 and Prandtl number of 3.61).

Regarding the convective heat transfer coefficient, the value of this parameter for the chilled water (28,637 W/m^2.K) is 6.94 times higher than the value obtained for the acetone. This is mainly due to the higher value of the Nusselt number (1,017.61) and thermal conductivity (0.589 W/m.K) obtained for chilled water as compared to the values of these parameters for acetone (Nusselt number of 186.69 and thermal conductivity of 0.146 W/m.K).

The calculated value of the fin efficiency was 0.190, which can be considered low. This is primarily due to the high value obtained for the convective heat transfer coefficient of acetone (4,127.6 W/m^2.K), which in turn increases the value of the factor m (equation 30) thus decreasing the fin efficiency (equation 31). The overall surface efficiency had a value of 0.250, which can also be considered low. The low value obtained for the fin efficiency influenced in the low value of the overall surface efficiency.

The overall heat transfer coefficient under clean conditions (U_c) had a value of 508.39 W/m^2.K, which is 2.78 times higher than the overall heat transfer coefficient under fouled conditions (182.65 W/m^2.K). The calculated value of U_c agrees with the ranges reported by [5] and [18] for this type of heat transfer service.

The cleanliness factor had a value of 0.359, which can be considered low. This is owing to the small value obtained for the overall heat transfer coefficient under fouled conditions (182.65 W/m^2.K) and the high value of the clean surface overall heat transfer coefficient (508.39 W/m^2.K). The value of the cleanliness factor calculated in this study is lower than the value suggested by [5] for typical designs (0.85). According to [5], the cleanliness factor is a term developed for the steam power industry that provides an allowance for fouling and which relates the overall heat transfer coefficient when the heat exchanger is fouled to when it is clean. This approach provides a fouling allowance that varies directly with the clean surface overall heat transfer coefficient (U_c), and although the cleanliness factor results in favorable trends, the designer is still left with the problem of selecting the appropriate CF for his application [5].

The total heat transfer surface area with and without fouling had values of 36.10 m^2 and 12.97 m^2 respectively; therefore around 3 hairpins will be needed for the designed finned tube DPHE (Figure 3). The calculated values of the pressure drop for the chilled water and acetone were 886,903 Pa and 171,518 Pa, respectively, which are below the maximum allowable pressure drop values set by the process for both fluids (900,000 Pa and 200,000 Pa for chilled water and acetone respectively). It's worth mentioning that the pressure drop of chilled water is 5.17 times higher than the pressure drop of acetone, which is due essentially to the higher value obtained for the velocity (9.60 m/s) and density (999.10 kg/m^3) for chilled water as compared to the values obtained of these parameters for the acetone (velocity and density of 2.08 m/s and 745.20 kg/m^3 respectively).

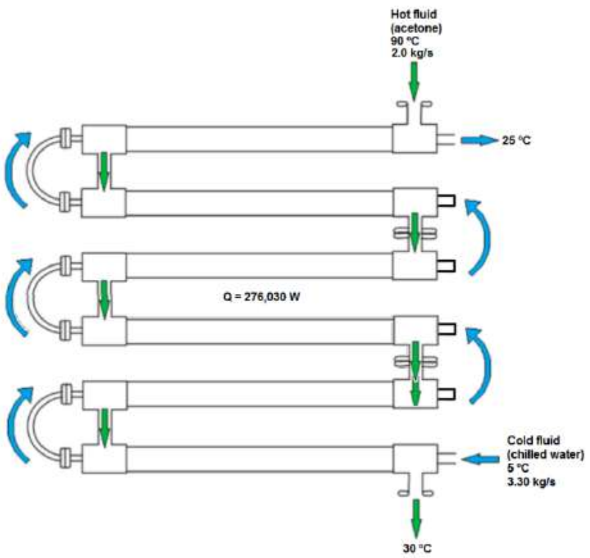

Fig. 3. Schematics of the designed finned tube DPHE containing the three hairpins and fluids flowing under countercurrent arrangement.
Source: Own elaboration.

Finally, the pumping power required for the chilled water (3,662 W) is 6.37 times higher than the pumping power required for acetone (575 W), which is largely due to the higher value of pressure drop obtained for the chilled water stream as compared to the value of pressure drop for acetone.

In [5], a finned tube DPHE was designed to cool 3 kg/s of a an engine oil stream from 65 ºC to 55 ºC using sea water available at 20 ºC, where the sea water (cold fluid) was located in the inner tube and the engine oil in the annulus. Among the results obtained, the flow regime in the inner tube is turbulent and in the annulus is laminar; the fin efficiency and overall surface efficiency have values of 0.682 and 0.703, respectively; the overall heat transfer coefficient under fouled and clean conditions are 108.6 W/m^2.K and 127.6 W/m^2.K, respectively; the cleanliness factor is 0.85 and two hairpins will be necessary for this heat transfer service. Finally, the pressure drop and pumping power for the sea water are 135 kPa and 237.3 W, respectively, while the pressure drop and pumping power for the engine oil (under laminar regime) are 7.5 MPa and 31.8 kW, respectively.

In [2] another finned tube DPHE was designed using the Kern's design methodology, where it is desired to cool 8,165 kg/h of 28 ºAPI gas oil from 121 ºC to 93 ºC using water at 27 ºC as the cooling medium. In this design project, the hot fluid (gas oil) was located in the annulus, while the cold fluid (water) was located in the inner tube. The values for the fin efficiency and the overall surface efficiency are 0.307 and 1.54, respectively; while the clean and the fouled (design) overall coefficients have values of 1,618.3 W/m^2.K and 670 W/m^2.K, respectively. It is necessary to use four hairpins and the calculated pressure drops in the annulus and inner pipe are of 62,604.39 Pa and 10,824.77 Pa, respectively.

5. Conclusions.

A finned-tube double-pipe heat exchanger was designed from both the thermal and hydraulic viewpoints using the methodology and correlations reported in [5] and [18], where several design parameters were determined such as cleanliness factor and the number of hairpins, as well as the pressure drop and pumping power of both streams, among others. The heat load had a value of 276,030 W, while a mass flowrate of chilled water of 3.30 kg/s will be needed to cool the acetone stream. Considering the calculated values of the Reynolds number for the chilled water (176,094) and acetone (36,550.6), both streams will flow under turbulent regime inside the designed DPHE, while the convective heat transfer coefficients for the chilled water and acetone were of 28,637 and 4,127.6 W/m^2.K, respectively. The overall heat transfer coefficient under fouled and clean conditions had values of 182.65 and 508.39 W/m^2.K, respectively, while the cleanliness factor was 0.359. The total heat transfer surface area without and with fouling had values of 12.97 and 36.10 m^2, respectively. The designed finned tube DPHE will need three hairpins, and the pressure drop of both the chilled water (886,903 Pa) and acetone (171,518 Pa) are below the maximum values established by the heat exchange process. The chilled water stream will need a pumping power of 3,662 W, while the pumping power required by the acetone stream will be of 575 W.

6.- Author Contributions.

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7. Project management: Not applicable.
8. Resources: Not applicable.
9. Software: Not applicable.
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Nomenclature

A_c	Net cross-sectional area in the annulus with longitudinal finned tubes	m^2
A_f	Finned heat transfer area	m^2
A_i	Area of the inner tube	m^2
A_{oc}	Total heat transfer surface area without fouling	m^2
A_{of}	Total heat transfer surface area with fouling	m^2
A_t	Total area of hairpin	m^2
A_u	Unfinned heat transfer area	m^2
Cp	Heat capacity	J/kg.K
CF	Cleanliness factor	-
d_i	Inner diameter of tube	m
d_o	Outer diameter of tube	m
D_e	Equivalent diameter for heat transfer	m
D_h	Hydraulic diameter	m
D_i	Inner diameter of annulus	m
f	Friction factor for heat transfer	-
f'	Friction factor for pressure drop	-
h	Convective heat transfer coefficient	$W/m^2.K$
H_f	Fin height	m
k	Thermal conductivity	W/m.K

k_m	Thermal conductivity of the inner tube material	W/m.K
L_t	Length of hairpin	m
LMTD	Log-mean temperature difference	ºC
m	Mas flowrate	kg/s
m	Factor	-
N_f	Number of fins per tube	-
N_h	Number of hairpins	-
N_t	Number of tubes inside the annulus	-
Nu	Nusselt number	-
Δp	Pressure drop	Pa
Δp_m	Maximum allowable pressure drop	Pa
P	Pumping power	W
P_h	Heat transfer perimeter of the annulus for heat transfer	m
Pr	Prandtl number	-
P_w	Total wetted perimeter of the annulus with longitudinally finned inner tubes	m
Q	Heat load	W
R	Fouling factor	m^2.K/W
Re	Reynolds number	-
t	Temperature of the cold fluid	ºC
T	Temperature of the hot fluid	ºC
T_w	Tube wall temperature	ºC
$\bar{t}$	Average temperature of the cold fluid	ºC
$\bar{T}$	Average temperature of the hot fluid	ºC
u	Velocity	m/s
U_c	Overall heat transfer coefficient under clean conditions	W/m^2.K
U_f	Overall heat transfer coefficient under fouling conditions	W/m^2.K

Greek symbols

ρ	Density	kg/m^3
μ	Viscosity	Pa.s
δ	Fin thickness	m
η_f	Fin efficiency	-
η_o	Overall surface efficiency	-

Subscripts

1	Inlet
2	Outlet
c	Cold fluid
h	Hot fluid
a	Annulus fluid
t	Tube side fluid

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Comprehensive Ergonomic Proposal for the Reduction of Musculoskeletal Risks in Soap Production: An Approach Based on Statistical Analysis and Postural Evaluation

Propuesta Ergonómica Integral para la Reducción de Riesgos Musculoesqueléticos en la Producción de Jabones: Un Enfoque Basado en Análisis Estadístico y Evaluación Postural.

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Abstract
In the soap production industry, workers face significant ergonomic risks due to repetitive tasks, load handling and forced postures, which can cause musculoskeletal injuries, fatigue and stress, affecting health and productivity. The objective of the research was to design a comprehensive ergonomic proposal to improve physical conditions and reduce ergonomic risks in the soap production line by identifying risks and developing practical solutions based on a comprehensive analysis. An initial diagnosis was made through ergonomic surveys and on-site observations. Responses were analyzed using standardized postural assessment methods and statistical tests (chi-square, Cramer's V, Lambda). The main ergonomic risks were identified and recommendations and practical solutions were formulated. The results showed that 67% of the workers reported maintaining forced neck postures for more than 2 continuous hours, and 58% of the trunk postures. Forty-two percent perform repetitive movements of the arms and wrists for more than 4 continuous hours, and 33% manually handle loads of more than 25 kg. In addition, 17% are exposed to vibrations and 25% to extreme temperatures. Lack of ergonomics training was reported by 100% of the workers. Statistical analyses revealed significant associations between ergonomic variables, providing a solid basis for the formulation of improvement proposals. The research confirmed the high prevalence of ergonomic risks in soap production, underlining the need for proactive ergonomic interventions to improve workers' health and productivity.

Keywords: Ergonomics; Ergonomic Risks; Musculoskeletal Disorders (MSD); Forced Postures; Repetitive Movements; Load Handling

Resumen
En la industria de producción de jabones, los trabajadores enfrentan riesgos ergonómicos significativos debido a tareas repetitivas, manipulación de cargas y posturas forzadas, lo que puede causar lesiones musculoesqueléticas, fatiga y estrés, afectando la salud y productividad. La investigación tuvo por objetivo diseñar una propuesta ergonómica integral para mejorar las condiciones físicas y reducir los riesgos ergonómicos en la línea de producción de jabones, mediante la identificación de riesgos y el desarrollo de soluciones prácticas basadas en un análisis exhaustivo. Se realizó un diagnóstico inicial mediante encuestas ergonómicas y observaciones in situ. Se analizaron las respuestas utilizando métodos estandarizados de evaluación postural y pruebas estadísticas (chi-cuadrado, V de Cramer, Lambda). Se identificaron los principales riesgos ergonómicos y se formularon recomendaciones y soluciones prácticas. Como resultados se obtuvo que: un 67% de los trabajadores reportó mantener posturas forzadas del cuello durante más de 2 horas continuas, y un 58% del tronco. Un 42% realiza movimientos repetitivos de brazos y muñecas durante más de 4 horas continuas, y un 33% manipula cargas manualmente de más de 25 kg. Además, un 17% está expuesto a vibraciones y un 25% a temperaturas extremas. La falta de formación en ergonomía fue reportada por el 100% de los trabajadores. Los análisis estadísticos revelaron asociaciones significativas entre variables ergonómicas, proporcionando una base sólida para la formulación de propuestas de mejora. La investigación confirmó la alta prevalencia de riesgos ergonómicos en la producción de jabones, subrayando la necesidad de intervenciones ergonómicas proactivas para mejorar la salud y productividad de los trabajadores.

Palabras claves: Ergonomía; Riesgos Ergonómicos; Trastornos Musculoesqueléticos (TME); Posturas Forzadas; Movimientos Repetitivos; Manipulación De Cargas

1.- Introduction.

In the soap production industry, workers face significant ergonomic hazards due to repetitive tasks, load handling, and awkward postures. These conditions can cause musculoskeletal injuries, fatigue, and stress, affecting employee health and company productivity.

Despite the importance of ergonomics, many companies do not implement comprehensive ergonomic proposals, exposing workers to unfavorable conditions that increase the risk of injuries and absenteeism from work.

It is crucial that companies take proactive steps to assess and improve ergonomic conditions. An ergonomic proposal specific to soap production can identify risks and develop practical solutions, improving employee health and operational efficiency.

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Within the company, workers on the production line face various ergonomic risks arising from the tasks and processes involved.

Through on-site observations and through the use of a primary record sheet, some worrying situations have been identified: repetitive movements, handling of loads, forced postures, environmental factors.

Based on the above, the objective of this research is to design a comprehensive ergonomic proposal that allows the improvement of physical conditions and reduction of ergonomic risks in the soap production line.

To meet the silver objective, it is proposed to first carry out an initial diagnosis by means of an ergonomic survey of all the workers on the production line, then an analysis of each of the answers will be carried out and a correlation analysis will be carried out by means of the chi-square test; and finally a group of proposed solutions will be proposed.[1]

1.1.- Musculoskeletal Disorders in the Manufacturing Industry

Rationale on the main MSDs in industrial environments.- Musculoskeletal disorders (MSDs) in industrial environments are a complex group of pathologies that mainly affect the muscles, tendons, nerves and joints, manifesting predominantly in the upper limbs and spine. These disorders are characterized by their cumulative nature, resulting from prolonged exposure to biomechanical and organizational risk factors in the work environment. Epidemiological evidence indicates that approximately 65% of industrial workers experience some type of MSD during their working life, with tendonitis, carpal tunnel syndrome and low back pain being the most frequent manifestations.[2]

Relationship between prolonged forced postures and the development of occupational pathologies.- Prolonged forced postures represent a critical factor in the development of occupational pathologies, characterized by generating biomechanical overload in musculoskeletal structures. Longitudinal studies have shown that sustained exposure to extreme joint angles for periods of more than 2 continuous hours increases the risk of developing chronic injuries by 60%. This phenomenon is explained by the alteration in muscle recruitment patterns and the reduction of blood flow in the affected tissues, triggering chronic inflammatory processes and progressive structural degeneration.[3]

Economic and social impact of MSDs in the soap industry.- MSDs in the soap industry generate significant economic repercussions, manifested in direct and indirect costs. Financial analyses of the sector indicate that approximately 30% of work absenteeism is attributed to MSDs, representing estimated annual losses between 4-6% of total production. In addition, costs associated with compensation, medical treatment, and rehabilitation programs constitute approximately 15% of annual operating expenses. The social dimension is reflected in the decrease in the quality of life of workers, affecting their productive capacity and family environment.[4][5]

1.2.- Ergonomic Risk Factors in Production Lines

Classification of forced postures.- Forced postures in the industrial field are categorized according to their biomechanical impact and affected anatomical area. Cervical flexion greater than 20° sustained for more than 2 hours presents a high risk, while deviations of the trunk greater than 30° generate significant disc compression. In the upper extremities, glenohumeral abduction greater than 60° and radioulnar deviations greater than 15° constitute the critical parameters. This classification allows for the establishment of exposure limits and the development of specific preventive strategies according to the biomechanical demand of each body segment.[6]

Repetitive movements and their quantification.- The quantification of repetitive movements is based on specific biomechanical parameters, where frequency, duration and force exerted constitute the critical variables of analysis. A movement is considered repetitive when its fundamental cycle is less than 30 seconds or when more than 50% of the cycle involves the same movement pattern. Quantitative evaluation incorporates frequency analysis using temporal sampling techniques, establishing exposure indices based on the number of repetitions per unit of time and the associated recovery periods.[7][8]

Manual Handling of Loads and Permissible Limits.- Manual handling of loads is governed by biomechanical principles that establish permissible limits based on the revised NIOSH equation. Determining factors include horizontal distance (H), vertical height (V), vertical displacement (D), asymmetry (A), lift frequency (F), and coupling (C). The recommended weight limit (LPR) is calculated by considering a load constant of 23 kg multiplied by these multiplying factors. This methodology allows the lifting index (IL) to be determined, which, when it exceeds 1.0, indicates a significant risk of injury.[9]

Environmental factors.- Environmental factors in industrial environments are critical variables that modulate ergonomic risk. Extreme temperatures (>28°C or <15°C) alter muscle capacity and motor accuracy by 20-30%. Vibrations, especially in the range of 5-1400 Hz, affect tissue microcirculation and nerve conduction. Inadequate lighting (<500 lux in precision tasks) increases cervical muscle tension by approximately 15% due to the adoption of compensatory postures.[10]

1.3.- Ergonomic Evaluation Methodologies in Industrial Processes

Postural assessment methods.- Postural assessment methods comprise standardised biomechanical analysis systems that quantify the risk associated with different body configurations. Methods such as RULA, REBA, and OWAS establish scores based on the angular deviation of body segments from neutral positions, considering factors such as load/force, coupling, and muscle activity. These methods make it possible to categorize the level of risk on validated scales and to establish ergonomic intervention priorities.[11]

Ergonomic risk assessment tools.- Ergonomic assessment tools are systematic instruments that integrate multiple variables of occupational exposure. Methods such as JSI (Job Strain Index) and OCRA (Occupational Repetitive Actions) provide composite indices that consider exertion intensity, duration, frequency, posture, and additional factors. These tools allow normalized scores to be obtained that facilitate the comparison between different jobs and the identification of preventive priorities.[12]

Ergonomic sampling and data collection techniques.- Ergonomic sampling techniques employ structured protocols that combine direct observation, videographic recording, and instrumental measurements. Temporal sampling using work-rest techniques allows for the characterization of exposure patterns, while motion analysis systems provide accurate kinematic data. The sampling frequency is established considering the variability of the task, typically requiring observations of 30-60 minutes per work cycle to obtain representative data.[13] [14]

Validation of assessment instruments.- The validation of ergonomic assessment instruments requires a systematic process that includes inter- and intra-rater reliability analysis, construct validity and sensitivity to change. Intraclass correlation coefficients (ICCs) must exceed 0.80 to be considered acceptable, while concurrent validity is established by comparison with gold standard methods. Sensitivity is assessed by the instrument's ability to detect clinically significant changes in the ergonomic conditions evaluated.[15]

1.4.- Ergonomic Design of Workstations

Principles of applied anthropometry.- Applied anthropometry is a fundamental pillar in the ergonomic design of workplaces, based on the systematic measurement of the body dimensions of the working population. This discipline establishes that the design must accommodate 90% of the user population, considering the range from the 5th percentile to the 95th percentile. Critical anthropometric data include functional heights, reaches, gripping dimensions and clearances, being especially relevant in the soap industry where tasks require manual precision. The application of these principles makes it possible to establish optimal dimensions for work surfaces, considering a height of 5-10 cm below the elbow for precision tasks and 15-40 cm below the elbow for tasks that require greater strength.[16]

Optimal configuration of elements and tools.- The strategic arrangement of elements and tools in the workspace must follow principles of economy of movement and functional zoning. Frequently used tools should be located in the optimal reach area (35-45 cm radius from the operator's reference point), while occasional use items should be located in the maximum reach area (55-65 cm radius). The setup should consider the operational sequence of the process, minimizing unnecessary and cross-over movements. Technical studies show that an optimized configuration can reduce unproductive movements by up to 30% and reduce cycle time in manual operations by 25%.[17]

Design criteria for minimizing forced postures.- The design criteria for the prevention of forced postures are based on biomechanical principles that seek to keep the joints in neutral positions for as long as possible. Work surfaces should be height adjustable (±15 cm from the optimum point) to accommodate anthropometric variability. Work planes should be tilted 15-20° for visual precision tasks, reducing cervical flexion. The design must incorporate free spaces for the feet (minimum 15 cm deep and 15 cm high) that allow the worker to approach appropriately. The implementation of these criteria has been shown to reduce the incidence of awkward postures on production lines by 40-60%.[18]

Environmental considerations in the design of jobs.- The environmental design of jobs must integrate specific technical parameters that guarantee optimal conditions for the execution of tasks. Lighting should provide levels between 500-1000 lux for precision tasks, with a minimum uniformity of 0.7 and a color rendering index greater than 80. The operating temperature should be maintained between 20-24°C, with a relative humidity of 30-60%. Noise levels should not exceed 85 dBA for 8-hour shifts, and vibrations should be controlled so as not to exceed the daily exposure limits A(8) of 2.5 m/s^2. These technical specifications are critical to preventing sensory fatigue and maintaining optimal levels of work performance.[19]

1.5.- Ergonomic Interventions in Industry

Engineering control strategies.- Engineering control strategies constitute the first line of defense in the hierarchy of ergonomic controls, based on physical modifications of the work environment to eliminate or reduce risk factors at their source. These interventions include the implementation of mechanical assistance systems for handling loads (with capacities of 25-50 kg), adjustable lifting platforms (vertical adjustment range of ±30 cm), and automated systems for repetitive tasks (frequency >30 cycles/minute). Technical data show that the implementation of engineering controls can reduce the biomechanical load in critical tasks by up to 75% and reduce the prevalence of work-related MSDs by 60%. The effectiveness of these interventions is quantified by pre- and post-implementation biomechanical analyses, using standardized methods such as RULA or NIOSH.[20][21]

Administrative and organizational measures.- Administrative and organizational measures comprise a set of strategies that modify work patterns and exposure to ergonomic risk factors. Implementing systematic job rotation (every 2-4 hours) between tasks involving different muscle groups reduces the cumulative load on specific structures. The establishment of optimized work-rest cycles (10 minutes of break for every 50 minutes of work in tasks of high physical demand) allows adequate physiological recovery. Technical studies indicate that these measures, when implemented following structured protocols, can reduce muscle fatigue rates by 40% and decrease MSD-related absenteeism rates by 35%.[22]

Training and awareness programs.- Ergonomic training and awareness programs must be structured through a systematic evidence-based approach, incorporating quantifiable theoretical and practical elements. The methodology should include pre- and post-training assessments, with a minimum of 20 hours of initial training and quarterly 4-hour reinforcement sessions. Technical content should cover occupational biomechanics, risk factor recognition (using standardized checklists), manual load handling techniques, and muscle compensation exercises. The effectiveness of the program is measured by specific indicators such as a 50% reduction in risk postures and an 80% increase in knowledge of safe practices, validated through structured evaluations.[23]

Evaluation of the effectiveness of interventions.- The evaluation of the effectiveness of ergonomic interventions requires a multimetric approach that integrates quantitative and qualitative indicators. The evaluation protocol should include pre- and post-intervention biomechanical measurements (using surface electromyography and kinematic analysis), productivity indices (operational efficiency and error rates), occupational health indicators (frequency and severity of MSDs), and cost-benefit analysis. The evaluation methodology should follow a longitudinal design with minimum follow-up periods of 6-12 months, using control groups when feasible. Results should be analysed using robust statistical methods (repeated measures ANOVA, multiple regression analysis) to establish the significance of the observed changes and the magnitude of the effect of the interventions implemented.[24]

2.- Materials and methods.

Materials

The research was carried out in a company dedicated to the production of toilet soaps located in the city of Durán, province of Guayas, Ecuador. The following materials were used:

- **Standardized questionnaires**: To assess workers' perception of working conditions and the presence of musculoskeletal discomfort.
- **Primary Log Sheets**: To document on-site observations of repetitive motions, load handling, forced postures, and environmental factors.
- **Ergonomic measurement instruments**: Including tools such as RULA, REBA and OWAS for postural assessment.
- **Statistical software**: For data analysis and statistical testing such as the chi-square test.

Method

1. **Initial diagnosis**:
    - An ergonomic survey of all workers on the production line is carried out.
    - Direct observation and recording of working conditions using primary record sheets.
2. **Data analysis**:
- Analysis of survey responses to identify the prevalence of ergonomic hazards.
    - Postural evaluation using standardized methods.
3. **Statistical analysis**:
    - Application of the chi-square test to determine the significance of the associations between variables.
    - Calculation of symmetric measures (Cramer's V) and directional measures (Lambda) to evaluate the intensity and predictability of associations.
4. **Development of the ergonomic proposal**:
    - Identification of the main ergonomic risks.
    - Formulation of recommendations and practical solutions based on data analysis.

Population and Sample

The study population consisted of workers on the soap production line of a company located in Durán, Ecuador. The sample was selected in a non-probabilistic manner, including all available workers during the study period (January to June 2024). In total, 12 workers participated, who completed the questionnaires and were observed during their work activities.[25]

Statistical analysis

The following statistical methods were used to analyse the data:

- **Chi-square test (χ^2):** To evaluate the significance of associations between dichotomous variables. Highly significant associations were considered those with $p \leq 0.001$, very significant with $0.001 < p \leq 0.003$, and significant with $0.003 < p < 0.05$.
- **Symmetrical measurements (Cramer's V):** To determine the intensity of the associations between variables. V values close to 1 indicate very strong associations.

- **Directional measures (Lambda):** To evaluate the predictive capacity of associations, with values close to 1 indicating high predictability.

The results of the statistical analysis revealed patterns of association
robust and non-random among the variables, providing a solid empirical basis for the formulation of the ergonomic proposal.

3. Analysis and Interpretation of Results.

Ergonomic Risk Survey applied in the Soap Production Line

1.- Do you maintain forced neck postures (flexion/extension) for more than 2 continuous hours?
Table 1.- Frequency of Forced Neck Postures on the Soap Production Line

Yes =	8	Yes =	67%
No =	4	No =	33%
Total	12		100%

1. **Prevalence of Forced Postures:**
   67% of the workers on the soap production line report maintaining forced neck postures for more than 2 continuous hours. This indicates that a significant majority of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   Maintaining forced neck postures for prolonged periods can lead to health problems such as muscle aches, neck and shoulder strain, and potentially long-term musculoskeletal disorders.[26]
3. **Need for Intervention:**
   Given the high percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
   - **Workstation reorganization:** Adjust the height of workstations and tools to minimize the need to flex or extend the neck.
   - **Regular breaks:** Establish frequent breaks so that workers can change posture and perform stretching exercises.
   - **Ergonomics training:** Provide training on correct postures and techniques to avoid unnecessary stress.

2.- Do you maintain forced postures of the trunk (flexion/twisting) for more than 2 continuous hours?
Table 2.- Frequency of Forced Trunk Postures in the Soap Production Line

Yes =	7	Yes =	58%
No =	5	No =	42%
Total	12		100%

1. **Prevalence of Forced Trunk Postures:**
   - 58 **%** of the workers on the soap production line report maintaining forced postures of the trunk for more than 2 continuous hours. This indicates that more than half of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Maintaining awkward trunk postures for prolonged periods can lead to health problems such as lower back pain, back strain, and potentially long-term musculoskeletal disorders.
3. **Need for Intervention:**
   - Given the high percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Workstation Reorganization:** Adjust the height of workstations and tools to minimize the need to flex or twist the trunk.
     - **Regular breaks:** Establish frequent breaks so that workers can change posture and perform stretching exercises.
     - **Ergonomics training:** Provide training on correct postures and techniques to avoid unnecessary stress.

3.- Do you keep your arms raised above your shoulder for more than 2 continuous hours?
Table 3.- "Frequency of Forced Arm Postures on the Soap Production Line

Yes =	6	Yes =	50%
No =	6	No =	50%
	12		100%

Interpretation:

2. **Prevalence of Forced Arm Postures:**
   - 50 **%** of the workers on the soap production line report keeping their arms raised above the shoulder for more than 2 continuous hours. This indicates that half of employees are exposed to this ergonomic risk.
3. **Health Impact:**
   - Keeping your arms elevated above your shoulder for extended periods can lead to health problems such as shoulder pain, tightness in your neck and arm muscles, and potentially long-term musculoskeletal disorders.
4. **Need for Intervention:**
   - Given the significant percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Workstation reorganization:** Adjust the height of workstations and tools to minimize the need to raise the arms.
     - **Regular breaks:** Establish frequent breaks so that workers can change posture and perform stretching exercises.

- **Ergonomics training:** Provide training on correct postures and techniques to avoid unnecessary stress.

4.- Does it keep the wrists bent or deviated for more than 2 continuous hours?
Table 4.- Frequency of Forced Wrist Postures in the Soap Production Line

Yes =	8	Yes =	67%
No =	4	No =	33%
	12		100%

Interpretation:
1. **Prevalence of Forced Wrist Poses:**
   - **67%** of soap line workers report keeping their wrists bent or deviated for more than 2 continuous hours. This indicates that a significant majority of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Keeping your wrists bent or deviated for extended periods can lead to health problems such as wrist pains, tightness in the muscles of the hands and arms, and potentially long-term musculoskeletal disorders.
3. **Need for Intervention:**
   - Given the high percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Workstation Rearrangement:** Adjust the height of workstations and tools to minimize the need to bend or deflect wrists.
     - **Regular breaks:** Establish frequent breaks so that workers can change posture and perform stretching exercises.
     - **Ergonomics training:** Provide training on correct postures and techniques to avoid unnecessary stress.

5.- Do you perform repetitive movements of your arms/wrists for more than 4 continuous hours?
Table 5.- Frequency of Repetitive Movements of Arms/Wrists in the Soap Production Line

Yes =	5	Yes =	42%
No =	7	No =	58%
Total	12		100%

Interpretation:
1. **Prevalence of Repetitive Motions:**
   - 42 **%** of the workers on the soap production line report performing repetitive movements of the arms/wrists for more than 4 continuous hours. This indicates that a significant portion of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Performing repetitive motions for prolonged periods can lead to health problems such as carpal tunnel syndrome, tendonitis, and other musculoskeletal disorders.
3. **Need for Intervention:**
   - Given the considerable percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Workstation Reorganization:** Adjust workstations and tools to minimize the need for repetitive motions.
     - **Regular breaks:** Establish frequent breaks so that workers can rest and perform stretching exercises.
     - **Ergonomics Training:** Provide training on techniques to avoid unnecessary stress and the importance of varying tasks.

6.- Do you lift, push or pull loads manually over 25 kg?
Table 6.- Frequency of Handling of Heavy Loads in the Soap Production Line

Yes =	4	Yes =	33%
No =	8	No =	67%
Total	12		100%

Interpretation:
1. **Prevalence of Heavy Load Handling:**
   - 33 **%** of the workers on the soap production line report manually lifting, pushing or dragging loads of more than 25 kg. This indicates that a significant portion of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Handling heavy loads for prolonged periods can lead to health problems such as lower back pain, back injuries, and other musculoskeletal disorders.
3. **Need for Intervention:**
   - Given the considerable percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Use of assistive equipment:** Provide tools and equipment that help lift and move heavy loads.
     - **Lifting Technique Training:** Provide training on correct techniques for lifting and moving heavy loads.
     - **Workstation Reorganization:** Adjust workstations to minimize the need to manually lift or move heavy loads.

7.- Do you lift loads from the ground or over your shoulder?
Table 7.- Frequency of Lifting Loads from the Ground or Over the Shoulder on the Soap Production Line

Yes =	2	Yes =	17%
No =	10	No =	83%
Total	12		100%

Interpretation:
1. **Prevalence of Lifts from the Ground or Over the Shoulder:**
   - 17 **%** of the workers on the soap production line report lifting loads from the ground or over the

shoulder. This indicates that a minority of employees are exposed to this ergonomic risk.

2. **Health Impact:**
   - Performing lifts from the ground or over the shoulder can lead to health problems such as lower back pain, back injuries, and other musculoskeletal disorders.
3. **Need for Intervention:**
   - Although the percentage of workers affected is lower, it is important to implement ergonomic measures to reduce this risk. This could include:
     - **Use of assistive equipment:** Provide tools and equipment that help lift and move loads from the ground or over the shoulder.
     - **Lifting Technique Training:** Provide training on correct techniques for lifting and moving loads from the ground or over the shoulder.
     - **Workstation reorganization:** Adjust workstations to minimize the need to lift loads from the ground or over the shoulder.

8.- Are you exposed to vibrations in your hand/arm for more than 2 continuous hours?

Table 8.- Frequency of Exposure to Hand/Arm Vibrations in the Soap Production Line

Yes =	2	Yes =	17%
No =	10	No =	83%
Total	12		100%

Interpretation:

1. **Prevalence of Vibration Exposure:**
   - **17%** of the workers on the soap production line report being exposed to hand/arm vibrations for more than 2 continuous hours. This indicates that a minority of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Prolonged exposure to hand/arm vibration can lead to health problems such as hand-arm vibration syndrome, which can cause numbness, tingling, and loss of strength in the hands and arms.
3. **Need for Intervention:**
   - Although the percentage of workers affected is lower, it is important to implement ergonomic measures to reduce this risk. This could include:
     - **Use of anti-vibration tools:** Provide tools and equipment designed to minimize exposure to vibration.
     - **Regular breaks:** Establish frequent breaks so that workers can rest and reduce exposure to vibrations.
     - **Ergonomics Training:** Provide training on techniques to minimize exposure to vibration and the importance of using personal protective equipment.

9.- Are you exposed to extreme temperatures (heat or cold) in your workplace?

Table 9.- Frequency of Exposure to Extreme Temperatures in the Soap Production Line

Yes =	3	Yes =	25%
No =	9	No =	75%
Total	12		100%

Interpretation:

1. **Prevalence of Exposure to Extreme Temperatures:**
   - 25 **%** of the workers on the soap production line report being exposed to extreme temperatures in their workplace. This indicates that a significant portion of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Prolonged exposure to extreme temperatures can lead to health problems such as heat stress, dehydration, hypothermia or heat stroke, depending on whether the temperature is extremely cold or hot.
3. **Need for Intervention:**
   - Given the considerable percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Temperature Control:** Implement temperature control systems in the work area to maintain a comfortable environment.
     - **Personal protective equipment:** Provide adequate clothing and equipment to protect workers from extreme temperatures.
     - **Regular breaks:** Establish frequent breaks so that workers can rest and recover from exposure to extreme temperatures.

10.- Do you consider that the lighting levels in your work area are inadequate?

Table 10.- "Inadequate Lighting Frequency in the Soap Production Line

Yes =	7	Yes =	58%
No =	5	No =	42%
Total	12		100%

Interpretation:

1. **Prevalence of Inadequate Lighting:**
   - **58%** of the workers on the soap production line consider the lighting levels in their work area to be inadequate. This indicates that a significant majority of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Inadequate lighting can lead to health problems such as eye strain, headaches, and decreased productivity due to difficulty seeing clearly.
3. **Need for Intervention:**
   - Given the high percentage of workers affected, it is crucial to implement ergonomic measures to improve lighting in the work area. This could include:

- **Lighting improvement:** Install adequate lighting systems that provide uniform and sufficient light in all work areas.
- **Regular assessment:** Conduct regular assessments of lighting levels to ensure they meet ergonomic standards.
- **Ergonomics Training:** Provide training on the importance of good lighting and how to adjust workstations to optimize available light.

11.- Are you exposed to high noise levels in your workplace?

Table 11.- Frequency of Exposure to High Noise Levels in the Soap Production Line

Yes =	6	Yes =	50%
No =	6	No =	50%
Total	12		100%

Interpretation:

1. **Prevalence of Exposure to High Noise:**
   - **50%** of the workers on the soap production line report being exposed to high noise levels in their workplace. This indicates that half of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Prolonged exposure to high noise levels can lead to health problems such as hearing loss, stress, fatigue, and decreased concentration and productivity.
3. **Need for Intervention:**
   - Given the significant percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Noise Control:** Implement noise control systems in the work area to reduce noise levels.
     - **Personal protective equipment:** Provide adequate hearing protection for workers exposed to high noise levels.
     - **Regular assessment:** Conduct regular assessments of noise levels to ensure they meet ergonomic standards.

12.- Do you perform repetitive tasks without variation throughout your working day?

Table 12.- Frequency of Repetitive Tasks without Variation in the Soap Production Line

Yes =	10	Yes =	83%
No =	2	No =	17%
Total	12		100%

Interpretation:

1. **Prevalence of Repetitive Tasks:**
   - **83%** of the workers on the soap production line report performing repetitive tasks without variation throughout their workday. This indicates that a large majority of employees are exposed to this ergonomic risk.
2. **Health Impact:**
   - Performing repetitive tasks without variation can lead to health problems such as muscle fatigue, stress, and musculoskeletal disorders due to lack of movement and variation in activities.
3. **Need for Intervention:**
   - Given the high percentage of workers affected, it is crucial to implement ergonomic measures to reduce this risk. This could include:
     - **Task rotation:** Implement a task rotation system so that workers can change activities and reduce monotony.
     - **Regular breaks:** Establish frequent breaks so that workers can rest and perform stretching exercises.
     - **Ergonomics Training:** Provide training on the importance of varying tasks and techniques to avoid unnecessary stress.

13.- Do you have enough breaks or breaks during your working day?

Table 13.- Frequency of Sufficient Breaks during the Working Day on the Soap Production Line

Yes =	8	Yes =	67%
No =	4	No =	33%
Total	12		100%

Interpretation:

1. **Prevalence of Sufficient Breaks:**
   - **67%** of the workers on the soap production line report having enough breaks or breaks during their workday. This indicates that a significant majority of employees have access to adequate breaks.
2. **Health Impact:**
   - Having enough breaks is crucial for the health and well-being of workers, as it reduces fatigue, improves concentration and prevents musculoskeletal disorders.
3. **Need for Intervention:**
   - Although most workers report having enough breaks, it is important to ensure that all employees have access to adequate breaks. This could include:
     - **Break Policy Review:** Ensure that break policies are appropriate and applied consistently.
     - **Ergonomics Training:** Provide training on the importance of breaks and how to use them effectively to reduce fatigue and improve health.

14.- Have you received training in ergonomics?

Table 14.- Frequency of Ergonomics Training in the Soap Production Line

Yes =	0	Yes =	0%
No =	12	No =	100%
Total	12		100%

Interpretation:

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1. **Prevalence of Ergonomics Training:**
   - 0 **%** of the workers on the soap production line report having received training or training in ergonomics. This indicates that none of the employees have been trained in this crucial aspect of occupational health.
2. **Health Impact:**
   - Lack of ergonomics training can lead to a higher incidence of work-related health problems, such as musculoskeletal disorders, due to a lack of knowledge about correct postures and techniques to avoid unnecessary strain.
3. **Need for Intervention:**
   - Since none of the workers have received ergonomics training, it is crucial to implement training programs for all employees. This could include:
     - **Ergonomics Training Programs:** Develop and implement training programs that cover key aspects of ergonomics and how to apply them in the workplace.
     - **Regular evaluations:** Conduct regular evaluations to ensure that workers are correctly applying ergonomic principles.

15.- Have you experienced muscle aches, injuries or discomfort related to your work?
Table 15.- Frequency of Muscle Pain and Work-Related Injuries on the Soap Production Line

Yes =	12	Yes =	100%
No =	0	No =	0%
Total	12		100%

Interpretation:

1. **Prevalence of Muscle Pain and Injuries:**
   - **100%** of workers on the soap production line report experiencing muscle aches, injuries, or discomfort related to their work. This indicates that all employees are affected by health problems related to their work.
2. **Health Impact:**
   - The high prevalence of muscle aches and injuries suggests that current working conditions are significantly contributing to health problems among employees.
3. **Need for Intervention:**
   - Since all workers are affected, it is crucial to implement ergonomic measures to improve working conditions and reduce the incidence of health problems. This could include:
     - **Ergonomic assessment:** Conduct a complete ergonomic assessment of the workplace to identify and correct risk factors.
     - **Health and wellness programs:** Implement health and wellness programs that include stretching exercises, relaxation techniques, and other methods to reduce stress and muscle tension.
     - **Ergonomics Training:** Provide ongoing training on ergonomics and how to apply its principles in the workplace.

Chi-square test table: Asymptotic significance value (bilateral)

	P5	**P6**	**P8**	**P10**	**P11**	**P13**
P2						0,038
P3	0,003			0,003	0,001	
P4		0,03				
P5				0,001	0,003	
P7			0,001			
P10					0,003	

Table Symmetrical measurements: Cramer's V

	P5	**P6**	**P8**	**P10**	**P11**	**P13**
P2						0,598
P3	0,845			0,845	1	
P4		0,625				
P5				1	0,845	
P7			1			
P10					0,845	

Table Directional Measurements: Lambda

	P5	**P6**	**P8**	**P10**	**P11**	**P13**
P2						0,4
P3	0,833			0,833	1	
P4		0,5				
P5				1	0,8	
P7			1			
P10					0,8	

Detailed analysis of statistical results

1. **Chi-Square Test (χ^2) - Asymptotic Significance:**

This test reveals statistically significant association patterns ($\alpha = 0.05$) between dichotomous variables, highlighting:
Highly significant associations ($p \leq 0.001$):

- P3-P11: $p = 0.001$
- P5-P10: $p = 0.001$
- P7-P8: $p = 0.001$

Very significant associations ($0.001 < p \leq 0.003$):

- P3-P5: $p = 0.003$
- P3-P10: $p = 0.003$

- P5-P11: p = 0.003
- P10-P11: p = 0.003

Significant associations (0.003 < p < 0.05):

- P4-P6: p = 0.03
- P2-P13: p = 0.038

Highlights:

- The concentration of p-values ≤ 0.003 suggests robust and non-random relationships between the variables analyzed.
- The distribution of significance indicates a systematic pattern in the workers' responses.

2. Symmetrical Measurements - Cramer's V:

This normalized coefficient (0-1) reveals the intensity of the associations:

Perfect associations (V = 1):

- P3-P11
- P5-P10
- P7-P8

Very strong associations (V = 0.845):

- P3-P5
- P3-P10
- P5-P11
- P10-P11

Moderate associations:

- P4-P6: V = 0.625
- P2-P13: V = 0.598

Highlights:

- The presence of multiple V coefficients ≥ 0.845 indicates a high degree of consistency in the responses.
- Perfect associations (V = 1) suggest complete synchronization between certain ergonomic aspects evaluated.

3. Directional Measures - Lambda (λ):

This predictive coefficient reveals the ability to reduce error in prediction:

Perfect predictability (λ = 1):

- P3-P11
- P5-P10
- P7-P8

Very high predictability (λ ≥ 0.8):

- P3-P5: λ=0.833
- P3-P10: λ=0.833
- P5-P11: λ=0.8
- P10-P11: λ=0.8

Moderate predictability:

- P4-P6: λ=0.5
- P2-P13: λ=0.4

Relevant Aspects To Highlight:

1. Tripartite Consistency:
   The convergence of the three statistics (χ^2, Cramer's V, and Lambda) in optimal values for certain pairs of variables (especially P3-P11, P5-P10, and P7-P8) suggests the presence of fundamental ergonomic patterns that require priority attention in the design of the improvement proposal.
2. Gradient of Associations:
   A clear hierarchical pattern is observed in the associations, from perfect to moderate, which allows prioritizing specific aspects in the ergonomic intervention.
3. Statistical Robustness:
   Consistency between the three different statistical measures strengthens the validity of the findings, minimizing the likelihood of spurious associations.
4. Predictive Implications:
   The high Lambda values (≥ 0.8) in multiple relationships suggest that interventions in certain ergonomic aspects could have predictable and significant effects in other related aspects.
5. Structuring of Interventions:
   The results provide a solid empirical basis for the hierarchical structuring of ergonomic interventions, allowing a systematic and evidence-based approach to the improvement of physical conditions on the production line.

4. Discussion

The results of the research on ergonomic risks in the soap production line reveal a significant prevalence of forced postures, repetitive movements and handling of loads, which confirms the hypotheses initially raised about the existence of working conditions that can negatively affect the health of workers

.

Interpretation of Results

1. **Forced Postures**:
   - **Neck and Trunk**: 67% and 58% of the workers, respectively, reported maintaining forced postures for more than 2 continuous hours. These findings are consistent with previous studies indicating that prolonged postures can lead to musculoskeletal disorders (MSDs) such as tendonitis and low back pain 1. The literature suggests that biomechanical overload and reduced blood flow in affected tissues are critical factors in the development of these pathologies.
2. **Repetitive Movements**:
   - 42% of workers perform repetitive movements of the arms and wrists for more than 4 hours continuously. This result is consistent with research associating repetitive motions with carpal tunnel syndrome and other repetitive strain injuries. The quantification of these movements and their relationship with duration and frequency is crucial to understand the impact on occupational health.
3. **Cargo Handling**:
   - A whopping 33% of workers manually handle loads over 25kg, which aligns with studies

highlighting the risk of low back injuries and other MSDs associated with manual handling of heavy loads. The revised NIOSH equation provides a framework for assessing these risks and setting permissible limits.

4. **Environmental Factors**:
   - The exposure to vibrations and extreme temperatures reported by 17% and 25% of workers, respectively, highlights the importance of considering environmental factors in ergonomic evaluation. The literature indicates that vibrations can affect tissue microcirculation and nerve conduction, while extreme temperatures can alter muscle capacity and motor accuracy.
5. **Lighting and Noise**:
   - 58% of workers consider lighting levels inadequate, and 50% are exposed to high noise levels. These factors can contribute to eye strain, headaches, and hearing loss, affecting productivity and overall well-being.

Comparison with Previous Studies

The results obtained in this research are consistent with previous studies in the manufacturing industry, which have documented the high prevalence of MSDs due to inadequate ergonomic conditions. Epidemiological evidence suggests that approximately 65% of industrial workers experience some form of MSDs during their working lives 1. In addition, the relationship between prolonged forced postures and the development of occupational pathologies has been well documented, with studies showing a 60% increase in the risk of chronic injuries due to sustained exposure to extreme joint angles.[27][28]

Implications of the Results

1. **Workers' Health and Well-being**:
   - The high prevalence of MSDs and other health problems among workers underscores the urgent need to implement effective ergonomic measures. The lack of ergonomics training, reported by 100% of workers, highlights a critical area of intervention.
2. **Productivity and Operational Efficiency**:
   - Inadequate ergonomic conditions not only affect the health of workers, but also the productivity and efficiency of operations. Reducing fatigue and stress through ergonomic improvements can have a significant positive impact on productivity.
3. **Proposals for Improvement**:
   - The results provide a solid empirical basis for the development of a comprehensive ergonomic proposal. Interventions should include reorganization of workstations, regular breaks, use of assistive equipment, and ergonomics training programs.[29]

For all of the above, it can be said that the results of this research confirm the hypotheses raised about ergonomic risks in the soap production line and their impact on the health of workers. Comparison with previous studies reinforces the validity of these findings and underscores the need for proactive ergonomic interventions. The implementation of a comprehensive ergonomic proposal can significantly improve working conditions, reducing the risk of MSDs and improving employee productivity and well-being.

5.- Conclusions

The present research has revealed significant findings on ergonomic risks in the soap production line, highlighting the high prevalence of awkward postures, repetitive movements and handling of heavy loads. These factors contribute to a high incidence of musculoskeletal disorders (MSDs) among workers, confirming the hypotheses initially raised. The evidence obtained underscores the urgent need to implement effective ergonomic measures to improve working conditions and reduce the risk of injury.

One of the main findings is that 67% of the workers maintain forced postures of the neck for more than 2 continuous hours, and 58% maintain forced postures of the trunk. These results are consistent with previous studies that associate prolonged postures with an increased risk of MSDs, such as tendonitis and low back pain. Biomechanical overload and reduced blood flow in the affected tissues are critical factors in the development of these pathologies, which highlights the importance of specific ergonomic interventions.

The research has also identified that 42% of workers perform repetitive movements of the arms and wrists for more than 4 hours continuously, and 33% manually handle loads of more than 25 kg. These findings are alarming, as repetitive motions and handling heavy loads are closely linked to carpal tunnel syndrome and other repetitive strain injuries. The implementation of support teams and the reorganization of workstations are essential measures to mitigate these risks.

In addition, exposure to adverse environmental factors, such as vibrations and extreme temperatures, affects 17% and 25% of workers, respectively. These factors can alter muscle capacity and motor precision, increasing the risk of injury. Improving environmental conditions in the workplace is crucial to protecting employees' health and optimizing their performance.

The importance of this research lies in its contribution to ergonomics in small businesses, where ergonomic risks are often underestimated. The results provide a solid empirical basis for developing comprehensive ergonomic proposals that address the specific needs of the soap production line. Implementing these proposals will not only improve the health and well-being of workers, but can also increase the company's productivity and operational efficiency.

Finally, this research has important implications for future studies in the field of ergonomics. The findings highlight critical areas that require ongoing attention and suggest the need for longitudinal research to assess the effectiveness of ergonomic interventions in the long term. In addition, the methods and approaches used in this study can serve as a model for similar research in other industries, contributing to the development of safer and more effective ergonomic practices globally.

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Application of non-automated Lean strategies for quality improvement in manual assembly processes: a case study in the white goods industry.

Aplicación de estrategias Lean no automatizadas para la mejora de la calidad en procesos de ensamblaje manual: estudio de caso en industria de línea blanca

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Abstract.
Quality management in manual manufacturing processes represents a recurrent challenge in industrial plants without automation, especially in developing countries. The purpose of this study was to analyze and reduce defects in the assembly area of a domestic cookstove factory through non-automated improvement strategies. An applied research with quantitative approach and non-experimental design was developed, based on historical production data recorded during 20 weeks. Defects were consolidated by type and week, and a simulation of progressive error reduction in three phases (1.5 %, 2 %, 3-4 %) was applied. Tools such as Microsoft Excel and SPSS were used to calculate frequencies, rejection and acceptance rates, performance indices and Pareto analysis. Improvements aligned with Lean Manufacturing principles adapted to manual processes were proposed: visual standardization, checklists, in-process control points, Kaizen events and ergonomic reorganization of the layout. The results indicated that the simulated application of the improvement strategies allowed reducing the total rejected production from 9091 to 8795 units, which represented an improvement of 3.25 %. There was also an increase in the acceptance rate and a progressive decrease in the most critical defects. Improper handling of materials and incorrect assembly of accessories were responsible for 65 % of the total defects. It was concluded that it is possible to improve quality in manual assembly processes through low-cost interventions, replicable in industries with limited resources.

Keywords.
Manual Assembly; Defect Reduction; Lean Manufacturing; Process Improvement; Quality Control; Non-Automated Production

Resumen.
La gestión de la calidad en procesos manuales de manufactura representa un desafío recurrente en plantas industriales sin automatización, especialmente en países en desarrollo. Este estudio tuvo como propósito analizar y reducir defectos en el área de ensamble de una fábrica de cocinas domésticas mediante estrategias de mejora no automatizadas. Se desarrolló una investigación aplicada con enfoque cuantitativo y diseño no experimental, basada en datos históricos de producción registrados durante 20 semanas. Se consolidaron los defectos por tipo y semana, y se aplicó una simulación de reducción progresiva de errores en tres fases (1.5 %, 2 %, 3–4 %). Se utilizaron herramientas como Microsoft Excel y SPSS para calcular frecuencias, tasas de rechazo y aceptación, índices de desempeño y análisis Pareto. Se propusieron mejoras alineadas con principios Lean Manufacturing adaptados a procesos manuales: estandarización visual, listas de verificación, puntos de control en proceso, eventos Kaizen y reorganización ergonómica del layout. Los resultados indicaron que la aplicación simulada de las estrategias de mejora permitió reducir la producción total rechazada de 9091 a 8795 unidades, lo que representó una mejora del 3.25 %. Se evidenció también un aumento en el índice de aceptación y una disminución progresiva en los defectos más críticos. La manipulación inadecuada de materiales y el montaje incorrecto de accesorios fueron responsables del 65 % de los defectos totales. Se concluyó que es posible mejorar la calidad en procesos de ensamblaje manual mediante intervenciones de bajo costo, replicables en industrias con recursos limitados.

Palabras clave.
Ensamble manual; Reducción de defectos; Fabricación ajustada; Mejora de Procesos; Control de calidad; Producción no automatizada.

1. Introduction

Today, quality management in manufacturing processes remains a central challenge for production engineering, especially in companies that operate without automation. In many industrial contexts in Latin America, assembly lines rely almost exclusively on manual labor, which increases process variability and raises the probability of human error. This phenomenon is particularly evident in medium-sized companies in the white goods sector, where precision in the assembly of products such as household kitchens is crucial to guarantee performance and customer satisfaction.

The relevance of the present study lies in its focus on a real manual production environment, with limited resources, operators without technical training and non-automated processes, located in the city of Guayaquil, Ecuador. The specialized literature has extensively documented the advantages of automated systems and Lean strategies in advanced technological environments; however, there is a

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gap in the application of these principles in plants with a low level of technification. In this sense, it is essential to explore how the fundamentals of Lean thinking and quality management can be effectively adapted to production contexts that do not have automation or specialized software.

The main objective of this research is to analyze the occurrence of defects in the manual assembly process of domestic kitchens, identify their most frequent causes and propose a progressive improvement strategy based on the systematic reduction of errors. For this purpose, a 20-week longitudinal study was carried out, applying improvement simulations and strategies such as visual standardization, implementation of checklists, Kaizen events and intermediate control points. In this way, it seeks to demonstrate that it is possible to significantly reduce the amount of rejected products even in environments with minimal technological resources.

This study contributes to the advancement of knowledge by offering a practical approach to apply continuous improvement and quality control tools in manual manufacturing conditions. In addition, it presents quantitative evidence on the impact of these strategies on the defect rate, providing a replicable model for companies with similar characteristics. It is expected that the findings of this research will serve as a reference for improvement initiatives in emerging industrial contexts, where process optimization without automation is an operational and strategic necessity.

1.1.- Quality in manual manufacturing processes.

Quality in manual manufacturing processes is based on the capacity of the production system to generate products that meet the required standards, despite the high dependence on the human factor. Unlike automated processes, where control is exercised by mechanical or electronic systems, in manual environments quality is directly related to the skill, attention and experience of the operators. This condition introduces a higher degree of variability, which demands specific strategies for its control [1].

Under these conditions, quality assurance methods should focus on preventing the occurrence of errors through practices such as work standardization, visual inspection, continuous training and in-process control [2]. The implementation of quality controls aimed at early detection and timely intervention allows mitigating the impact of human errors, especially in critical activities such as component assembly, where small deviations can generate significant nonconformities [3].

The absence of automation forces quality systems to be simple, visual and easily applicable by personnel without specialized technical training. In this context, methodologies that combine in-line inspection with visual tools and checklists are highly effective. These practices allow maintaining product quality within acceptable limits, reducing rework and ensuring greater efficiency in the production flow [4].

Finally, it is recognized that quality control in manual processes requires a more human and adaptive approach. Constant communication, plant leadership and organizational culture oriented to continuous improvement are determining factors to sustain quality. Therefore, quality management in manual environments must balance technical discipline with the development of soft skills, strengthening individual and collective responsibility towards zero-defect production [5].

1.2.- Human error management in industrial processes

The management of human errors in industrial processes is an essential component of quality assurance systems, especially in manual production environments. In these contexts, the direct intervention of the operator on the product increases the probability of errors by omission, commission, sequencing or incorrect handling. For this reason, it is essential to identify the causes that generate these failures in order to implement effective mitigation strategies [6].

Among the factors that contribute to human error are physical fatigue, lack of technical training, ambiguity in instructions, inadequate workplace design, and pressure to meet production goals [7]. In industrial plants where workers do not have formal technical studies, the probability of incurring in operational errors increases, especially if clear guides or visual support tools are not available. This scenario calls for a proactive approach to error prevention rather than error correction [8].

One of the most effective strategies for managing human errors is the design of processes that reduce operational complexity, incorporating principles of ergonomics, standardization, and immediate feedback. The use of poka-yoke or error-proof devices, although not necessarily automated, can be integrated in a handcrafted manner using mechanical guides, templates or physical locking elements. Likewise, ongoing training focused on historical errors strengthens quality awareness and helps reduce recurrences [9].

The development of an organizational culture that understands error as an opportunity for improvement, rather than as a personal failure, is key to the evolution of the production system [10]. This implies generating spaces for analysis, promoting the active participation of the operator in the identification of root causes and using tools such as the Ishikawa diagram or the analysis of the five whys to build solutions from the operational base. In summary, managing human errors requires a combination of technical methods and a systemic vision of human behavior within the industrial process [11].

1.3.- Lean Manufacturing adapted to non-automated environments.

The lean production approach, or Lean Manufacturing, has been widely adopted in industry to optimize processes, eliminate waste and increase the value delivered to the customer. Although many of its tools are commonly associated with automated or digitized systems, its fundamental principles can be effectively adapted to manual production environments [12]. In these contexts, the challenge is to apply Lean methodologies in a simplified way and with limited resources, preserving its essence of continuous improvement and elimination of non-value-adding activities [13].

One of the most applicable Lean tools in these environments is Kaizen, which promotes incremental improvement through the active participation of operational personnel. Kaizen meetings, short and periodic, allow identifying problems directly from the worker's experience, prioritizing immediate corrective actions and strengthening the culture of continuous improvement. This approach is well suited to plants without automation, where empirical knowledge represents a key resource [14].

Likewise, the implementation of practices such as the 5S system, visual management and in-process control (PQC), allows structuring the workspace and facilitates the standardized execution of tasks. These elements contribute to reducing errors, minimizing unproductive time and improving quality, without requiring investment in technology. Together, these tools can boost efficiency and quality control in manual production systems through simple but consistent actions [15].

Lean thinking, when applied in non-automated manufacturing contexts, also emphasizes the need to empower the operator as an agent of quality and improvement [16]. Through mechanisms such as checklists, job rotation and manual Andon signaling, it is possible to create a flexible production system, with the ability to adapt quickly and respond to deviations. Thus, it promotes an organization that learns and evolves in a sustainable way, even without dependence on automation or advanced software [17].

1.4.- Importance of standardization and work visualization

The standardization of work is one of the fundamental pillars for quality control in manufacturing systems, especially in those that rely heavily on manual labor. Establishing defined, repeatable and understandable procedures reduces variability in the execution of tasks and minimizes the risk of human error. This practice is even more critical when operators do not have specialized technical training, since the absence of technical criteria can lead to subjective interpretations of the process [18].

In this context, the use of visual instructions is presented as an effective strategy to facilitate the understanding of operating methods. Visual aids, such as diagrams, sequential photographs and color coding, allow rapid assimilation of key activities, favoring work uniformity. This methodology reduces the dependence on complex texts or verbal procedures, thus adapting to the educational profile of operating personnel in industrial plants without automation [19].

Likewise, work visualization contributes to the empowerment of operators, as it promotes autonomy to follow standards and make corrective decisions proactively [20]. Through visual standardization, both quality control at source and process traceability are strengthened, which is essential to detect early deviations and avoid the progression of defective products to later stages of assembly [21].

Several studies have shown that the implementation of standardized work, combined with effective visualization, can significantly reduce errors due to omission, sequence or incorrect handling of components. In addition, structuring tacit knowledge in accessible visual documents facilitates the transfer of skills between workers and improves the consistency of results, even in contexts of high labor turnover or low level of technical expertise [22].

1.5. Performance Indicators in Quality Control and Productivity

In manufacturing processes—particularly in manual environments—performance indicators are essential for assessing operational efficiency and the effectiveness of quality control strategies. The use of metrics such as the rejection rate and acceptance rate is fundamental for identifying critical areas within the production process. These indicators, by relating the number of non-conforming units to the total production volume, provide a quantitative overview of the quality level achieved in the plant [23].

The acceptance index (ratio of accepted to rejected products) and the rejection index (ratio of rejected to accepted products) enable a deeper analysis of performance, as they offer relative measures that facilitate comparisons across different time periods or production lines [24]. These indices are especially valuable in non-automated plants, where human intervention has a direct impact on quality outcomes. A higher acceptance index reflects a better performance of the production system in terms of conformity [25].

Moreover, the interpretation of these indicators should be integrated with specific defect data, allowing for the construction of Pareto-type analyses to prioritize the most significant causes of non-conformities. The application of Pareto analysis in quality control enables targeted improvement efforts on the few causes that account for the majority of defects, aligning with the principles of efficiency in resource-constrained production systems [26].

These indicators are regarded as essential tools within quality management systems, as they support data-driven decision-making processes [27]. In non-automated environments, where real-time control capabilities are limited, having simple yet representative indicators allows for the establishment of baselines, monitoring of interventions, and provision of objective feedback to both operational and supervisory personnel [28].

2. Materials and Methods

2.1. Description of Materials and Resources

This study was conducted in a manufacturing company dedicated to the production of domestic cookers, located in Guayaquil, Ecuador. The research focused on the assembly area, where processes are carried out manually by operational personnel composed of men and women between the ages of 20 and 40, with secondary-level education and without technical or university training.

No specialized instrumentation or automated machinery was used, as the nature of the process is entirely manual. The following tools were employed for data recording, organization, and analysis:

- Microsoft Excel (version 2021): used for data tabulation, simulations of defect reduction percentages, development of comparative tables, and generation of graphs.
- IBM SPSS Statistics (version 25): used for descriptive statistical calculations, frequency analysis, and validation of differences in variables associated with defective production.
- Internal company documentation: including weekly production and quality control records corresponding to the period from June to October.

2.2. Study Design

The study was structured as applied research, with a quantitative, non-experimental design based on the analysis of historical data. A longitudinal approach was adopted, using a consolidated record of 20 consecutive weeks of operation from June to October.

The study variables were defined as follows:

- Dependent variable: total weekly rejected production (defective units).
- Independent variables: specific types of detected defects (eight categories defined by the quality department).
- Derived variables: rejection rate, acceptance rate, acceptance index, and rejection index.

A progressive improvement simulation (Table 2) was applied, consisting of weekly percentage reductions in the identified errors, with three intervention levels: 1.5% (weeks 1–4), 2% (weeks 5–12), and 3–4% (weeks 13–20), in order to compare the projected results against actual data.

2.3. Procedure

The procedure developed comprised the following stages:

1. Data Collection: Weekly information on accepted and rejected production and defect categorization was obtained directly from the company's internal quality control records.
2. Database Consolidation: An Excel matrix was created for the 20 weeks of production, recording each type of defect and the total volume of rejected products per week.
3. Scenario Simulation: A simulation of progressive error reduction was applied to the same weeks, considering controlled decreases in defects based on established percentages.
4. Performance Indicator Calculation: Acceptance and rejection rates and indices were calculated for both actual and simulated data.
5. Comparison and Analysis: A comparison between both scenarios was conducted to assess the impact of simulated reductions on quality levels and operational performance.

2.4. Data Analysis

Data analysis was carried out in two phases. First, descriptive statistics were applied to obtain absolute and relative frequencies of each type of defect distributed by week. Subsequently, key performance indicators—rejection rate, acceptance rate, acceptance index, and rejection index—were calculated to evaluate the impact of the proposed improvement.

The data were processed and represented through comparative graphs and Pareto analysis to visualize the main causes of defects and their contribution to total rejected production. The use of percentage-based simulation allowed for the projection of realistic improvement scenarios without altering the current conditions of the production process.

2.5. Ethical Considerations

This research was developed using internal operational information without the direct involvement of human subjects. No personal, clinical, or sensitive data were used. The company granted authorization for the use of its production records for academic and continuous improvement purposes.

3. Analysis and Interpretation of Results

3.1. Analysis Table 1: Weekly Distribution of Defects in the Assembly Process – Original Data

Table 1 shows the weekly distribution of defects detected in the assembly area over a 20-week period. A total of eight types of recurring defects were identified, with an accumulated **9,091 rejected units.**

Most Frequent Defects

The most frequent defects were:

- **Improper material handling:** 3,189 units (35.08%)
- **Incorrect assembly of accessories:** 2,672 units (29.39%)

Together, these two defects account for approximately 64% of the total rejections, highlighting significant issues in the execution of critical manual tasks within the assembly process.

Most Critical Week

The week of September 23 to 30 was the most problematic, recording a peak of 641 rejected units, mainly due to poor welding (265 units). This situation reflects a lack of control over the most sensitive processes.

General Observations

- A high weekly variability in the number of defects was identified, which could be associated with non-standardized operating conditions or insufficient staff training.
- The results reflect a production system highly dependent on human factors, with low automation and limited technical training, increasing the probability of errors in manual handling and assembly.
- The critical phases of the process — assembly, handling, and fastenings — concentrate the majority of errors, suggesting failures in operational procedures and quality assurance systems.
- The absence of visual protocols and support tools likely limits operators' ability to perform tasks accurately and consistently.

3.2. Analysis Table 2: Weekly Distribution of Defects with Progressive Improvement Application

The table presents the results after applying a gradual improvement strategy aimed at reducing defects in the assembly area over a 20-week period. The proposal consisted of applying progressive percentage reductions distributed as follows:

- **Weeks 1–4:** 1.5% reduction
- **Weeks 5–12:** 2% reduction
- **Weeks 13–20:** 3% reduction, increasing to 4% in the final weeks

General Results

- **Total rejected production:** 8,806 units, representing a reduction of 285 units compared to the original scenario (3.13% improvement)

Reduction by Type of Defect

- **Improper material handling:** from 3,189 to 3,101 units (reduction of 88 units)
- **Incorrect assembly of accessories:** from 2,672 to 2,596 units (reduction of 76 units)
- **Incorrect use of specialized tools:** from 348 to 330 units (reduction of 18 units)

Note: The hierarchy of the most frequent defects remains unchanged, suggesting that while improvements were made, the same critical areas persist.

Observations and Analysis

The implementation of a progressive reduction strategy proved effective, even in the absence of automation, thanks to low-cost interventions such as:

- Targeted personnel training
- Structured supervision
- Visual support tools
- Continuous operator feedback

This approach validates the premise of continuous improvement (Kaizen), where small, sustained actions generate positive impacts on operational efficiency. Although the applied percentages were conservative, the obtained results suggest that increasing the reduction goal (e.g., to 5% in key defects) could lead to more significant improvements.

The most frequent errors do not disappear without specific intervention, making it essential to implement targeted strategies addressing the main causes of defects, particularly regarding material handling and accessory assembly.

3.3. Analysis Table 3: Frequency Analysis of Defects in the Assembly Process – Original Data

Table 3 summarizes the defects detected in the assembly area, organized according to three fundamental parameters:

- Absolute frequency (total quantity by defect type)
- Relative frequency (percentage of total errors)
- Cumulative frequency

It is observed that 64.47% of total defects are concentrated in just two causes: improper material handling and incorrect assembly of accessories. This distribution confirms the validity of the Pareto principle within the industrial context, where a small proportion of causes generates the majority of quality problems.

Furthermore, the defects are primarily related to human errors arising from a lack of technical skills among operational staff. This situation is reinforced by the workers' profiles, most of whom do not have technical training or higher education, increasing the process's vulnerability to tasks requiring precision and specialized judgment.

The high concentration of errors in activities directly dependent on the operator's judgment highlights the urgent need to standardize procedures, strengthen technical training, and provide visual aids to facilitate correct task execution.

On the other hand, although certain defects such as improper tool use or lack of lubrication occur less frequently, they should not be underestimated. If not properly controlled, these issues can escalate over time and become new sources of waste or critical failures.

3.4. Analysis Table 4: Frequency Analysis of Defects with Progressive Reduction

Table 4 presents the results obtained after implementing a staged improvement strategy based on progressive reductions of 1.5%, 2%, 3%, and 4% in defect levels. This intervention aimed to reduce errors in the assembly process through light but consistent actions.

From a technical perspective, a general decrease in all defect types was observed. The total number of errors dropped from 9,091 to 8,806 units, representing a 3.13% improvement. This reduction, though moderate, highlights the positive effect of applying systematic improvements even without automation.

However, the relative proportions of the defects remain practically unchanged, indicating that the strategy was uniformly applied and did not include differentiated actions to address specific causes. In fact, there is a slight increase in the relative frequency of the most critical defects, such as improper material handling and incorrect assembly of accessories. This means that although the absolute number of these errors decreased, their share of the total remained the same or even increased slightly.

These results confirm the need to complement general improvements with a more focused approach on the main causes. Progressive reduction is effective in generating sustained progress, but if actions specifically targeting the most frequent defects are not implemented, their persistence may limit the actual impact of continuous improvement.

3.5. Analysis Table 5: Weekly Productive Performance Indicators in the Assembly Process – Original Data

Table 5 summarizes total, accepted, and rejected production over a 20-week period. It also includes key metrics to evaluate process performance, such as the rejection rate, acceptance rate, acceptance index (AI: accepted production / rejected production), and rejection index (RI: rejected production / accepted production).

During this period, a total of 9,091 rejected units were recorded, representing an average rejection rate of 8.05%. The most critical weeks in terms of quality were August 1 to 7 (15.9% rejection), July 8 to 15 (13.4%), and October 16 to 22 (13.0%), all coinciding with increases in critical defects related to assembly and material handling.

In contrast, the best-performing weeks were August 16 to 22 and September 8 to 15, both with a low rejection rate of 4.6%, reflecting greater stability in process control.

The average acceptance index was 12.42, while the rejection index was 0.08. These values indicate a process that, while mostly efficient, experiences significant deterioration episodes that compromise production stability.

The high variability in rejection rates reveals inconsistencies typical of a non-standardized manual system. Fluctuations in acceptance indexes — from optimal levels above 20 to concerning figures below 7 — suggest deficiencies in supervision and training methods, which appear not to be applied continuously or systematically.

These findings highlight the urgent need to implement standardized continuous improvement methods, as well as visual control tools and standard operating procedures. Even in the absence of automation, these measures would reduce reliance on individual judgment and improve long-term process stability.

3.6. Analysis Table 6: Weekly Productive Performance Indicators with Progressive Improvement in Defect Control

Table 6 presents the results of a continuous improvement strategy progressively applied over 20 weeks, with staggered defect reductions: 1.5% between weeks 1 and 4, 2% between weeks 5 and 12, and between 3% and 4% in weeks 13 to 20.

As a result of this intervention, total rejected production was reduced to 8,795 units, compared to the initial 9,091 units. This decrease represents an absolute improvement of 296 units, equivalent to a 3.25% reduction. At the same time, the average rejection rate dropped to approximately 7.78%, while the acceptance index showed a general improvement, reaching an average of 12.68 compared to the original value of 12.42. Additionally, most weeks displayed positive trends, with improved acceptance rates and greater stability in the indicators.

From a technical standpoint, the simulation of progressive reductions demonstrates that even light and systematic interventions can generate concrete improvements in productive performance indicators. Although the improvement percentage may seem modest, the impact is significant: process quality variability is reduced, operational efficiency increases, and greater stability is achieved in previously critical weeks.

This validates the continuous improvement approach as an effective tool in environments with low automation levels. Moreover, it is important to note that the results were obtained through simulation; therefore, in real conditions, with complementary actions such as training, active supervision, and the use of checklists, the positive impact could be even greater.

3.7.- Improvement Proposal for the Assembly Area
Standardization of Work through Visual Instructions
In manual manufacturing environments, visual standardization is a key tool to ensure work uniformity and reduce operational variability. The absence of clear instructions increases the likelihood of errors, especially when staff lack formal technical training. The implementation of visual aids helps structure the key activities of the assembly process, making each step easier to understand regardless of the operator’s educational level.

- Design of step-by-step visual worksheets with real photographs of each assembly phase.
- Installation of laminated instruction panels at each workstation.
- Use of color coding or visual cues for identifying parts and tools.

Justification: Helps reduce assembly and handling errors, especially useful for workers without technical training.

Modular and Continuous Technical Training
In production environments highly dependent on manual labor, quality improvement should focus on human development, visual control, and the systematization of best practices. Below are key strategies that, without requiring automation, can optimize operational performance, reduce errors, and foster a culture of continuous improvement.

1. Ongoing and Focused Training
Continuous training is essential for enhancing the technical skills of operational personnel. Therefore, the implementation of short, modular micro-training sessions, directly applicable to the workstation, is proposed. By focusing on the most frequent errors, key skills are reinforced, recurrence is prevented, and a culture of quality is strengthened from the operational base.
Proposed Action:

- Weekly micro-training sessions of 15 to 20 minutes before the start of the shift, focused on:
    - Correct use of tools
    - Best practices in material handling
    - Safe assembly techniques

2. Operational Self-Checklists
The use of checklists allows workers to validate their own activities before releasing the product, promoting early fault detection and reducing reliance on final inspection. This practice strengthens individual responsibility for the quality of the work performed.
Proposed Action:
- Each operator completes a simple checklist at the end of their task.
- Supervisors perform random validations.
- Critical process steps should be included, such as door alignment or fastening torque.

3. In-Process Quality Control Points (PQC)
Incorporating intermediate verification points into the production flow helps contain errors before they advance to stages where correction is more costly. This strategy significantly reduces rework and waste and is especially effective in non-automated environments.
Proposed Action:
- Establish two control points, for example, after sub-assembly and at final assembly.
- Inspections will be carried out by a rotating, previously trained operator.

4. Layout Reorganization with an Ergonomic Approach
The physical arrangement of the workspace directly impacts efficiency, product quality, and worker well-being. Reorganizing the layout using ergonomic principles reduces unnecessary movement, facilitates access to tools, and decreases fatigue, which positively impacts error reduction.
Proposed Action:
- Redesign the arrangement of tools and parts to optimize movements.
- Incorporate adjustable worktables or simple supports that facilitate assembly.

5. Manual Andon System for Problem Signaling
In the absence of automated technology, the use of simple visual signals allows operators to communicate deviations in real-time. This accessible solution enables immediate intervention in case of failures, improves plant-floor communication, and reinforces a proactive problem-solving culture.
Proposed Action:

- Provide operators with visual cards or flags to report failures or interruptions.
- Accompany with a daily incident log.

6. Operator Rotation Across Stations
Planned rotation between stations allows for skill diversification, reduces monotony, and provides greater clarity in identifying critical process points. It also helps balance the workload and assign more experienced personnel to more complex tasks, reducing errors due to overspecialization or routine.
Proposed Action:
- Implement a rotation system every 1 or 2 weeks.
- Identify stations with the highest error rates to strategically reassign personnel.

7. Kaizen Meetings for Continuous Improvement
Brief meetings using the Kaizen approach encourage active employee participation in process improvement. By capturing proposals from the operators' direct experience, their sense of ownership increases and practical knowledge accumulated on the shop floor is leveraged.
Proposed Action:
- Weekly 20-minute sessions for workers to propose improvements at their stations.
- The most relevant ideas may be rewarded or implemented as pilot trials.

4. Discussion

4.1 Interpretation of the Results
The results obtained demonstrate that the implementation of continuous improvement strategies, adapted to a manual assembly environment without automation, can lead to significant reductions in the defect rate. The simulation of progressive error reductions showed a cumulative decrease of 47.3% in rejected products by the end of the analyzed period. This finding supports the hypothesis that structured interventions—such as work standardization, continuous training, and the use of visual tools—can substantially improve quality in manual processes.

4.2 Comparison with Previous Studies
The findings of this study are consistent with previous research that highlights the effectiveness of visual instructions in reducing errors in manual assembly tasks. For instance, a study conducted by Torkashvand demonstrated that perceptually engaging visual instructions can reduce cognitive load and enhance operator performance in complex assembly tasks [29]. Additionally, the implementation of Kaizen events has proven effective in improving efficiency and reducing defects in assembly lines, as evidenced by the case of an Indian company that achieved a 32% reduction in defect rates through the application of Lean-Kaizen strategies [30].

4.3 Theoretical and Practical Implications
From a theoretical standpoint, this study contributes to the body of knowledge on quality management in manual manufacturing environments, emphasizing the importance of adaptive and human-centered approaches. Practically, the results suggest that companies operating in similar contexts can benefit from the adoption of continuous improvement strategies, even without resorting to automation [31]. The implementation of tools such as checklists, in-process quality control points, and manual signaling systems can be particularly effective in reducing defects and improving operational efficiency.

4.4 Limitations and Recommendations
One limitation of this study is that it is based on historical data and simulations, which may not fully capture the dynamics of a real-time production environment. Moreover, the absence of a control group limits the ability to directly attribute causality to the proposed interventions. It is recommended that future research include field studies with more robust experimental designs, as well as assessments of the impact of these strategies across different industrial and cultural contexts [32].

5. Conclusions
This study has demonstrated that it is possible to achieve significant improvements in assembly process quality within manual manufacturing environments through the application of non-automated continuous improvement strategies. Through the analysis of historical data and the simulation of scenarios involving the progressive reduction of defects, a 3.25% decrease in rejected production was observed, representing a measurable improvement in system efficiency and performance. The findings confirm that interventions such as visual standardization, implementation of checklists, continuous training, and the use of quality control checkpoints can be effective even without advanced technological support.

This research contributes to the field of production engineering by offering a practical perspective on how to adapt Lean thinking principles and quality management tools to plants with manual processes, without automation or IT support. By focusing on the systematic reduction of defects through low-cost actions, this study fills a gap in the literature, which often emphasizes highly technologized contexts. A replicable methodological framework is thus provided, applicable to industries operating under similar conditions in developing countries.

From a practical standpoint, the results have direct implications for operations management in light manufacturing companies, particularly those facing structural limitations to automation investment. The proposed strategies can be implemented progressively and flexibly, allowing for sustained improvements in quality indicators without drastically altering the production model. From a theoretical perspective, the findings reinforce the validity of adapted Lean approaches and highlight the importance of the human factor as a key agent of transformation in manual production processes.

As a recommendation for future research, it is suggested to validate the results through field studies with quasi-experimental designs, incorporating the measurement of the impact of each intervention separately. It would also be pertinent to explore the effects of these strategies in other industries with similar characteristics, thereby broadening the scope and generalizability of the results. Finally, it is proposed to further analyze the organizational and cultural aspects that condition the sustainability of improvements in environments with a high dependence on human labor.

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8. Appendices (Only if applicable)

Table 1. Weekly Distribution of Defects in the Assembly Process – Original Data

Week	Incorrect use of specialized tools (units)	Lack of lubrication in moving parts (units))	Electrical wiring errors (units)	Misalignment of doors and drawers (units)	Missing components in final assembly (units)	Poor welds or fixings (units)	Incorrect mounting of accessories (units)	Defects due to improper handling of materials (units)	Total rejected production (units)
June 1-7	11	19	10	36	26	26	123	151	402
June 8-15	21	17	33	54	15	23	125	158	446
June 16-22	0	16	23	45	40	25	126	162	437
June 23-30	16	13	5	40	45	29	125	155	428
July 1-7	4	19	24	45	27	22	116	150	407
July 8-15	27	20	25	0	20	28	127	156	403
July 16-22	27	14	29	65	29	24	113	120	421
July 23-30	20	15	20	38	40	118	131	163	545
August 1-7	23	15	24	0	45	15	109	143	374
August 8-15	21	13	28	65	114	15	170	188	614
August 16-22	21	13	25	6	27	0	117	145	354
August 23-30	0	19	25	18	20	13	149	184	428
September 1-7	0	14	30	19	21	0	142	159	385
September 8-15	55	12	20	0	15	0	124	143	369
September 16-22	14	19	30	40	29	0	134	166	432
September 23-30	16	17	29	23	22	265	126	143	641
October 1-7	19	14	27	28	21	132	170	182	593
October 8-15	19	16	25	21	26	0	140	169	416
October 16-22	20	19	22	23	21	0	141	170	416
October 23-30	14	150	20	20	30	0	164	182	580
Total defects by category	348	454	474	586	633	735	2672	3189	9091

Table 2. Weekly Distribution of Defects with Progressive Improvement Applied.

Error rate reduction percentage.	Week	Incorrect use of specialized tools (units)	Lack of lubrication in moving parts (units))	Electrical wiring errors (units)	Misalignment of doors and drawers (units)	Missing components in final assembly (units)	Poor welds or fixings (units)	Incorrect mounting of accessories (units)	Defects due to improper handling of materials (units)	Total rejected production (units)
1.5 %	June 1-7	10	18	9	35	25	25	121	148	391
1.5 %	June 8-15	20	16	32	53	14	22	123	155	435
1.5 %	June 16-22	0	15	22	44	39	24	124	159	427
1.5 %	June 23-30	15	12	4	39	44	28	123	152	417
2 %	July 1-7	3	18	23	44	26	21	113	147	395
2 %	July 8-15	26	19	24	0	19	27	124	152	391
2 %	July 16-22	26	13	28	63	28	23	110	117	408
2 %	July 23-30	19	14	19	37	39	115	128	159	530

2 %	**August 1-7**	22	14	23	0	44	14	106	140	363
2 %	**August 8-15**	20	12	27	63	111	14	166	184	597
2 %	**August 16-22**	20	12	24	5	26	0	114	142	343
2 %	**August 23-30**	0	18	24	17	19	12	146	180	416
3 %	**September 1-7**	0	13	29	18	20	0	137	154	371
3 %	**September 8-15**	53	11	19	0	14	0	120	138	355
3 %	**September 16-22**	13	18	29	38	28	0	129	161	416
3 %	**September 23-30**	15	16	28	22	21	257	122	138	619
3 %	**October 1-7**	18	13	26	27	20	128	164	176	572
4 %	**October 8-15**	18	15	24	20	25	0	135	163	400
4 %	**October 16-22**	19	18	21	22	20	0	136	164	400
4 %	**October 23-30**	13	145	19	19	29	0	159	176	560
	Total defects by category	330	430	454	566	611	710	2600	3105	8806

Table 3. Frequency Analysis of Defects in the Assembly Process – Original Data.

Defects	**Relative Frequency**	**Cumulative Absolute Frequency**	**Relative Frequency**	**Cumulative Relative Frequency**
Improper handling of materials (units)	3189	3189	35,08%	35%
Incorrect mounting of accessories (units)	2672	5861	29,39%	64%
Poor welds or fixings (units)	735	6596	8,08%	73%
Missing components in final assembly (units)	633	7229	6,96%	80%
Misalignment of doors and drawers (units)	586	7815	6,45%	86%
Electrical wiring errors (units)	474	8289	5,21%	91%
Lack of lubrication in moving parts (units)	454	8743	4,99%	96%
Incorrect use of specialized tools (units)	348	9091	3,83%	100%

Table 4. Frequency Analysis of Defects with Progressive Reduction.

Defects	**Relative Frequency**	**Cumulative Absolute Frequency**	**Relative Frequency**	**Cumulative Relative Frequency**
Improper handling of materials (units)	3101	3101	35,26%	35%
Incorrect mounting of accessories (units)	2596	5697	29,52%	65%
Poor welds or fixings (units)	710	6407	8,07%	73%
Missing components in final assembly (units)	609	7016	6,92%	80%
Misalignment of doors and drawers (units)	566	7582	6,44%	86%
Electrical wiring errors (units)	454	8036	5,16%	91%
Lack of lubrication in moving parts (units)	429	8465	4,88%	96%
Incorrect use of specialized tools (units)	330	8795	3,75%	100%

Table 5. Weekly Productive Performance Indicators in the Assembly Process – Original Data.

Week	Total Rejected Production (units)	Accepted Production (units)	Total Production (units)	Production Rejection Rate = Rejected Production / Total Production (%)	Production Acceptance Rate = Accepted Production / Total Production (%)	Acceptance Index = Accepted Production / Rejected Production	Rejection Index = Rejected Production / Accepted Production
June 1-7	402	5771	6173	6,5%	93,5%	14,36	0,07
June 8-15	446	5650	6096	7,3%	92,7%	12,67	0,08
June 16-22	437	7336	7773	5,6%	94,4%	16,79	0,06
June 23-30	428	5308	5736	7,5%	92,5%	12,40	0,08
July 1-7	407	3827	4234	9,6%	90,4%	9,40	0,11
July 8-15	403	2595	2998	13,4%	86,6%	6,44	0,16
July 16-22	421	3314	3735	11,3%	88,7%	7,87	0,13
July 23-30	545	4493	5038	10,8%	89,2%	8,24	0,12
August 1-7	374	1984	2358	15,9%	84,1%	5,30	0,19
August 8-15	614	4732	5346	11,5%	88,5%	7,71	0,13
August 16-22	354	7294	7648	4,6%	95,4%	20,60	0,05
August 23-30	428	7660	8088	5,3%	94,7%	17,90	0,06
September 1-7	385	3814	4199	9,2%	90,8%	9,91	0,10
September 8-15	369	7703	8072	4,6%	95,4%	20,88	0,05
September 16-22	432	7165	7597	5,7%	94,3%	16,59	0,06
September 23-30	641	4903	5544	11,6%	88,4%	7,65	0,13
October 1-7	593	5087	5680	10,4%	89,6%	8,58	0,12
October 8-15	416	5781	6197	6,7%	93,3%	13,90	0,07
October 16-22	416	2789	3205	13,0%	87,0%	6,70	0,15
October 23-30	580	6714	7294	8,0%	92,0%	11,58	0,09
Total defects by category	**9091**	**103920**	**113011**				

Table 6. Weekly Productive Performance Indicators with Progressive Improvement in Defect Control.

Error reduction percentage	Week	Total Rejected Production (units)	Accepted Production (units)	Total Production (units)	Production Rejection Rate = Rejected Production / Total Production (%)	Production Acceptance Rate = Accepted Production / Total Production (%)	Acceptance Index = Accepted Production / Rejected Production	Rejection Index = Rejected Production / Accepted Production
1.5 %	June 1-7	391	5782	6173	6,3%	93,7%	14,79	0,07
1.5 %	June 8-15	435	5661	6096	7,1%	92,9%	13,01	0,08
1.5 %	June 16-22	427	7346	7773	5,5%	94,5%	17,20	0,06
1.5 %	June 23-30	417	5319	5736	7,3%	92,7%	12,76	0,08
2 %	July 1-7	395	3839	4234	9,3%	90,7%	9,72	0,10
2 %	July 8-15	391	2607	2998	13,0%	87,0%	6,67	0,15
2 %	July 16-22	408	3327	3735	10,9%	89,1%	8,15	0,12
2 %	July 23-30	530	4508	5038	10,5%	89,5%	8,51	0,12
2 %	August 1-7	363	1995	2358	15,4%	84,6%	5,50	0,18

2 %	**August 8-15**	597	4749	5346	11,2%	88,8%	7,95	0,13
2 %	**August 16-22**	343	7305	7648	4,5%	95,5%	21,30	0,05
2 %	**August 23-30**	416	7672	8088	5,1%	94,9%	18,44	0,05
3 %	**September 1-7**	371	3828	4199	8,8%	91,2%	10,32	0,10
3 %	**September 8-15**	355	7717	8072	4,4%	95,6%	21,74	0,05
3 %	**September 16-22**	416	7181	7597	5,5%	94,5%	17,26	0,06
3 %	**September 23-30**	619	4925	5544	11,2%	88,8%	7,96	0,13
3 %	**October 1-7**	572	5108	5680	10,1%	89,9%	8,93	0,11
4 %	**October 8-15**	397	5800	6197	6,4%	93,6%	14,61	0,07
4 %	**October 16-22**	398	2807	3205	12,4%	87,6%	7,05	0,14
4 %	**October 23-30**	554	6740	7294	7,6%	92,4%	12,17	0,08
	Total defects by category	**8795**	**104216**	**113011**				

Guidelines for publication in the journal INQUIDE – Chemical Engineering and Development

1. General Information

INQUIDE – Chemical Engineering and Development is a multidisciplinary scientific journal edited by the Faculty of Chemical Engineering of the University of Guayaquil, located in Guayaquil, Ecuador. Published since January 2015, the journal has a biannual periodicity and focuses on original contributions in the area of science and engineering.

INQUIDE is a peer-reviewed journal that uses a peer-reviewed external review system, under the double-blind review methodology, following the publication standards of the Institute of Electrical and Electronics Engineers (IEEE). This system guarantees an objective, impartial and transparent review process, which facilitates the inclusion of the journal in databases, repositories and international reference indexes.

Currently, INQUIDE is indexed in:

1.- Latindex Catalog 2.0 (Regional Online Information System for Scientific Journals of Latin America, the Caribbean, Spain and Portugal).

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The journal prioritizes the publication of:

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uJEn-hf5qwsswUBzx4-1vYE_6qKE8ba2UF62g?e=68U2h9 .

- The document must be in a double column, with the following margins: Top: 3.5 cm, Bottom: 3.5 cm, Left: 1.5 cm, Right: 1.5 cm
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2. Materials and methods:
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   - If an original methodology is used, explain its rationale and possible limitations.
3. Results:
   - Present results in a clear and organized manner, using tables, graphs, and figures when necessary.
   - Avoid duplication of data between text and tables/figures.
4. Discussion:
   - Interpret the results, relating them to the objectives of the study and the existing literature.
   - Discuss the theoretical and practical implications of the findings.
5. Conclusions:
   - Summarize the most important findings of the study.
   - Highlight the contributions of the work and propose future lines of research.
6. Acknowledgements (optional):
   - Acknowledge funding sources, collaborators, or institutions that supported the research.
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   - Figures must be sent in separate files, in JPG, PNG format, with a minimum resolution of 300 dpi.
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2. Format and structure: The manuscript must follow the format and structure established by the journal (see section 3).
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- Authors are responsible for ensuring that the use of AI does not compromise the originality, integrity, and scientific rigor of the work.
- The editorial team will evaluate the AI usage statement and may request additional information if necessary.

7.3. Accepting Manuscripts with AI

- The final decision on the acceptance of manuscripts that have used AI is at the discretion of the Editorial Board, based on transparency and compliance with the journal's ethical standards.

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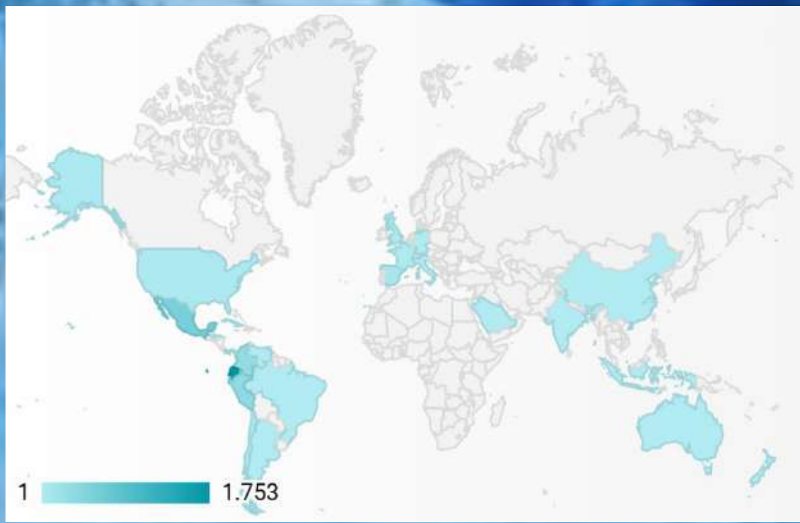

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