STEAM DISTRIBUTION SYSTEM: A DISCUSSION ON ENERGY LOST DURING OPERATION

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Abstract. *The current situation of supply and demand for natural resources (water, fuel) and energy has created an alert situation for society, especially for the industrial sector. The sustainable use of natural resources is essential to reductions in production costs. This work aims to demonstrate and discuss best practices to operate more efficiently and correctly a steam distribution system, reducing energy waste, fuel costs, environmental impacts and increasing operational reliability and the industry's sustainability. A case study was built with a process simulation to show the effect of the use of accessories (thermal insulator and steam traps) in conjunction with the pipes project on increasing energy efficiency in the steam system. These practices will demonstrate the importance and influence of both the situations in the operating costs of a company.*

Keywords: *Steam system, good practices, energy efficiency, industrial sustainability*

1. INTRODUCTION

The steam distribution system is responsible for transporting the steam generated by the boilers to final consumers, supplying sufficient quantities of steam at temperatures and pressures appropriate to the applications. They are responsible for much of the thermal and electrical energy supplied to industrial processes. The vapor transported is considered a basic input of great importance to the production chain and are inserted for example, in direct or indirect heating, as a driving force in equipment (turbines, pumps, compressors, air blowers), in the control pressure, in vacuum production in ejectors, cleaning equipment or materials, as raw material, among others. The water vapor overcomes all other fluids when it comes to their availability, stability, cost, safety and heat transfer capacity.

Given the current scenario of aggravation and intensification of environmental impacts, the steam distribution system has become a great potential for performance improvements and waste reductions. Within this theme, the main contributors to the economic and environmental impacts of the steam system are directly linked to pressure drop and energy and low efficiency system. These mass and energy waste has increased oconsumo of fossil fuels and water resources, emphasizing the emissions of greenhouse gases (GHG) and worsening water availability problems through pollution and high consumption.

Steam system project and good maintenance practices and operation are the main factors to increase efficiency. Some practices are directly linked to the performance of the entire steam system (generation, distribution and recovery) and will be addressed in this work, such as: (1) boiler water treatment; (2) boiler energy efficiency; (3) projects, layout and accessories; (4) steam quality; (5) deaerator operation; (6) drainage; (7) shutdown and start-up of sites.

2. GOOD PRACTICES: ENERGY EFFICIENCY INCREASE

2.1 Boiler water treatment

The treatment of water used for steam generation is a practice used to ensure the quality of the steam and the lifetime of the equipments and materials of the steam system and their respective consumers. As the steam generators (boilers) were increasing their importance and their operating conditions have become more critical, water quality also followed the same way. The raw water coming from the nature brings dissolved or suspended large quantities of impurities, hence the need for constant preventive treatment (Rothbarth, 2010). The preliminary treatment acts on the coarser impurities (turbidity, suspended solids, organic material) and depending on the need, more sophisticated treatments are performed to reduce dissolved materials. The most widely used methods for the preliminary treatment of the water are: (1) clarification/filtration; (2) ion exchange processes (subsidence, demineralization); (3) reverse osmosis; (4) deaeration. In the absence of water pretreatment the main consequences generated in steam system are: (a) corrosion; (B) incrustation; (C) drag water to steam, all reducing thermal and operating efficiency of the system and increase the risk of accidents (Trovati, 2004).

2.2 Boiler energy efficiency

The boilers are the main suppliers of thermal energy for the productive sector. Because of its importance to production and critical conditions of operation are considered major potential for improvement and increase efficiency. With the intense use of fuel for steam generation there is often energy losses in the process. The energy efficiency of steam generators is to make the most of the energy supplied by the combustion, reducing energy waste, bringing economic benefits, environmental and improvement of competitiveness. According to Nogueira (2005), the efficiency of a boiler can be calculated in two different ways: (1) direct method: directly assesses the amount of power generated in the form of steam by the amount of energy supplied by the fuel; (2) indirect method, calculates from main existing energy losses in the boiler, such as: (a) losses through the chimney; (b) losses associated with dry gases; (c) losses associated with the vapor present in the chimney; (d) loss by incomplete combustion of fuel; (e) loss by radiation and convection; (f) losses blowdown; (g) losses on fuel unconverted. However, for practical reasons and ease of obtainment of variables of the steam generation system, Eq. (1) below (direct method) can be applied to calculate the boiler efficiency:

$$\eta = \frac{m_v \cdot \left(h_{ae} - h_{vs}\right)}{m_c \cdot PCI} \tag{1}$$

Where,
η = boiler efficiency by direct method
m_v = mass flow of steam (kg/h)
h_{ae} = water enthalpy in the boiler input (kJ/kg)
h_{vs} = steam enthalpy in the boiler outlet (kJ/kg)
m_c = fuel mass flow (kg/h)
PCI = power lower calorific fuel (kJ/kg)

Some practices are required and others may be applied to make the boiler operation more efficient and economical, for example: i) increase the concentration cycles; ii) reuse of energy lost in the blowdown process; iii) external insulation; iv) Implementation of auxiliaries equipments (superheater, air preheater, economiser); v) audits/inspections; vi) maintenance; vii) type of fuel used; viii) project; among others.

2.3 Projects, layout and accessories

Often companies do not give due attention to the preliminary stages of projection, design and installation of the steam line and accessories, making the operation little productive and uneconomical. The steam lines are typically not designed as a whole, passing by expansions over time according to the process capability change without global analysis, resulting in the emergence of deadlines, tubes and accessories tangles and hazards of undershoots, increasing unnecessarily the losses of load and energy. The network layout projection step and the projection of the respective accessories must be carried out carefully and according to the process conditions and equipments. Some of the more important criteria are taken into consideration, for example: (1) operating conditions (pressure, temperature, steam rate); (2) load losses; (3) diameter and nominal thickness of the pipe; (4) draining the network; (5) type of materials pipe; (6) secondary branches; (7) accessories (steam trap, thermal insulation, valve, filter, gasket, support, others).

When it comes to accessories, each performs particular function and influence on the operational performance of the steam network. However, two main accessories are highlighted by its importance and significant interference in the energy efficiency of the system: the steam traps and thermal insulation. According to Telles (2001), the steam trap is an automatic device that separates and removes the condensate formed in line and heating equipment, without escape the live steam. To obtain good operating performance and reductions in energy losses, the steam traps need to be: (a) suitably selected and/or dimensioned, based on factors: steam and condensate operatinal (pressure, temperature), quantity of condensate formed, loss allowed live steam, occurring water hammers or vibrations, serviceability, cost, among others; (b) properly positioned, in closed end points, low points and rising elevations, linear stretches every 30 to 50 m, before the valves and close to the entrance of any equipment that does not work with condensate (Nogueira, 2005; Sarco, 2005; Watson, 2016).

Thermal insulation is one of the essential accessories in combating energy losses to the environment, conserving the heat energy and increasing efficiency in the system, supporting sustainable development, reducing the consumption of fuel and water. There are variety of insulating materials that can be deployed in a line, but the best choice must be made based on evaluation of the thermal needs. Are considered aspects such as: i) surface temperature; ii) Life time of the material; iii) thermal conductivity; iv) installation costs and heat loss; v) absorption material; among others. According to the insulation efficiency can be calculated amount of condensate formed in steam line through the Eq. (2) (Sarco, 2005; Zattoni, 2008).

$$Q = \frac{A \cdot U \cdot (T_{sat} - T_2) \cdot L \cdot (1 - E)}{C_l} \tag{2}$$

Where,
Q = condensate formed per hour due to energy losses to the environment (kg/h)
A = outer area of the tube per meter length (m²/m)
U = overall coefficient of heat transfer $(kJ/(h.m^2.°C)^{-1})$
T_{sat} = steam saturation temperature at the operating pressure (°C)
T_2 = environment temperature (°C)
L = length of piping (m)
E = thermal insulation efficiency
C_l = latent heat of the steam operating pressure (kJ/kg)

2.4 Steam quality

The high quality steam, in addition to increasing the efficiency and sustainability, helps reduce some problems that can cause economic losses and competitiveness for the company. The increase in the consumption of fuel and water, maintenance and frequent repairs to the line and equipment, increased risk of accidents, losses of mass and energy are some examples of damage caused by the poor quality of the produced steam. Some practices are associated with the quality of the vapor and assists in good operability of the system and increases productivity, for example: (1) implementation of an efficient water treatment for steam generation, reduces damage by corrosion, fouling and drag steam; (2) good operating and energy performance of the steam generator keeps the steam in proper operating condition, preventing moisture drag, excessive energy losses and increase in fuel consumption; (3) accessory facilities (steam traps, moisture separators, filters), reduces moisture, condensate and impurities present in the vapor and in the line.

2.5 Deaerator operation

According to Mikhailov (2012), the presence of air in the vapor stream directly affects their quality, making it difficult and reducing heat transfer, increasing the chances of corrosion and reducing system efficiency. The water feeding a boiler has a percentage of dissolved oxygen, and other compounds, such as bicarbonate, that the heat of the action, releases CO_2 that precipitated generates deposits. According Trovati (2004), the deaeration process of (mechanical) occurs in the preliminary treatment step, by means of the deaerator, when working at high temperatures, can eliminate much of the O_2 dissolved. Then, by chemical deaeration can removed the remaining portion, may also be performed by adding chemical compounds able to remove sufficiently the dissolved oxygen. The air must be eliminated in much as possible as they may cause some structural and operational problems, such as: (1) reducing the temperature of the steam, therefore reducing the partial pressure of steam in the presence of air in the steam flow; (2) resistant air film formation, reducing the steam heat transfer to the exchanging surface due to the low thermal conductivity of the film; (3) corrosion due to the presence of O_2 and CO_2.

2.6 Drainage

There are as the vapor is condensed in the line due to the existing heat exchange between the steam and the metal walls of the system, it is necessary to remove. Although the process of condensation being able to produce the largest portion of the heat to the process, the formed condensate may lead to reduced thermal efficiency and lead to problems such as: (1) increase in moisture in the steam; (2) reduction the temperature of the steam; (3) reduction in heat transfer; (4) water hammers; (5) materials damage (corrosion, fouling, erosion); among others. For these reasons, it is necessary practice for minimization of such problems through actions such as: (a) drainage installation points at appropriate locations (potentials condensate accumulation); (b) the ideal steam trap selection for the application; (c) piping inclination in the flow direction; (d) correct projections (accessories, main pipes, secondary branches) (Sarco, 2005).

The recovery and condensate return improves the energy efficiency of the system, reusing condensate and waste heat to reduce costs and local environmental impacts. The condensate reuse is an essential practice because: i) reduces water costs for supply; ii) reduces energy losses and hence fuel consumption; iii) reduces treatment costs of the boiler feed water; iv) reuses the waste energy for heating; v) generates low pressure steam (flash steam); vi) reduces waste and possible treatment costs thereof; among others. An alternative to reuse the recovered hot condensate involves the use of the flash vase. In this equipment, the pressure therein is reduced, providing a certain amount of low pressure steam (Nogueira, 2005; Sarco, 2005). To determine the amount of steam that can be recovered from the condensate, is used to Eq. (3) below:

$$\% \, \mathrm{Re}\!-\!evaporation = \frac{CSa - CSb}{CLb} \tag{3}$$

Where,
CSa = sensible heat of high pressure (kJ/kg)
CSb = sensible heat of low pressure (kJ/kg)
CLb = latent heat of low pressure (kJ/kg)

2.7 Shutdown and start-up of sites

Situations shutdown and start-up of sites can occur for predetermined measures, for periodic achievements of equipment maintenances, or emergency situations. When referring to the steam system, the boiler is primarily responsible for the stops due to its high degree of risk to human security, requiring greater attention. However, these interruptions can cause economic problems and intensify environmental damages. In a more specific vision, impact on the competitiveness of the company, the risk of accidents in the energy and material losses can be observed. Practices as we have seen in previous sections can avoid such downtime and increase system reliability.

In a start-up, when the steam is released in the cold distribution system is soon formed a large amount of condensate, because the steam in this heat is initially used to heat the metal walls of the pipe. The amount of condensate generated at the initial moment of heating can be calculated by Eq. (4).

$$Q = \frac{t \cdot 0{,}125 \cdot (T_1 - T_2) \cdot L}{C_l} \tag{4}$$

Where,
Q = amount of condensate formed (kg)
t = mass per meter of pipe to be heated (kg/m)
T_1 = steam temperature at the operating conditions (°C)
T_2 = environment temperature (°C)
L = length of heated piping (m)
C_l = latent heat of steam (kJ/kg)

3. CASE STUDY – DESIGN PARAMETERS

This case study aims to demonstrate and validate through a process simulator the importance of good practice in a simplified steam distribution system, showing the main opportunities for improvement and reduction of energy losses and savings in water consumption and fuel. Some of the main practices were listed in item 2 of this work, however, will be treated only the main responsibles for the losses in the steam system and energy efficiency the same: steam traps, thermal insulation and piping project.

In the example, the boiler provides superheated steam flow rate of 67 ton/h, with a pressure of 43.6 kgf/cm² and 259 °C, to heat exchangers located about 2 km away from the source. This steam feeds seven heat exchangers of a particular plant, under conditions of saturation of 33 kgf/cm² pressure and temperature of 240 °C. The steam flows are distributed to the heat exchangers as described in Tab. 1.

Table 1. Steam consumption of heat exchangers with pressure of 33 kgf/cm² and temperature of 240 °C.

TAG	MASS FLOW (ton/h)	TAG	MASS FLOW (ton/h)	TAG	MASS FLOW (ton/h)
TC-101	21.8	TC-104	2.1	TC-106	1.8
TC-102	9.4	TC-105	13.2	TC-107	7.2
TC-103	11.5	TOTAL = 67.0 ton/h			

Figure 1 below shows in simplified form a diagram representing the vapor system, with the stages of generating, distributing and steam consumption, besides the condensate recovery process formed in the system. This work will focus mainly on steam distribution system, bringing discussions about the practice of using steam traps, insulation and the choice of nominal diameter, both related to the energy efficiency of the system.

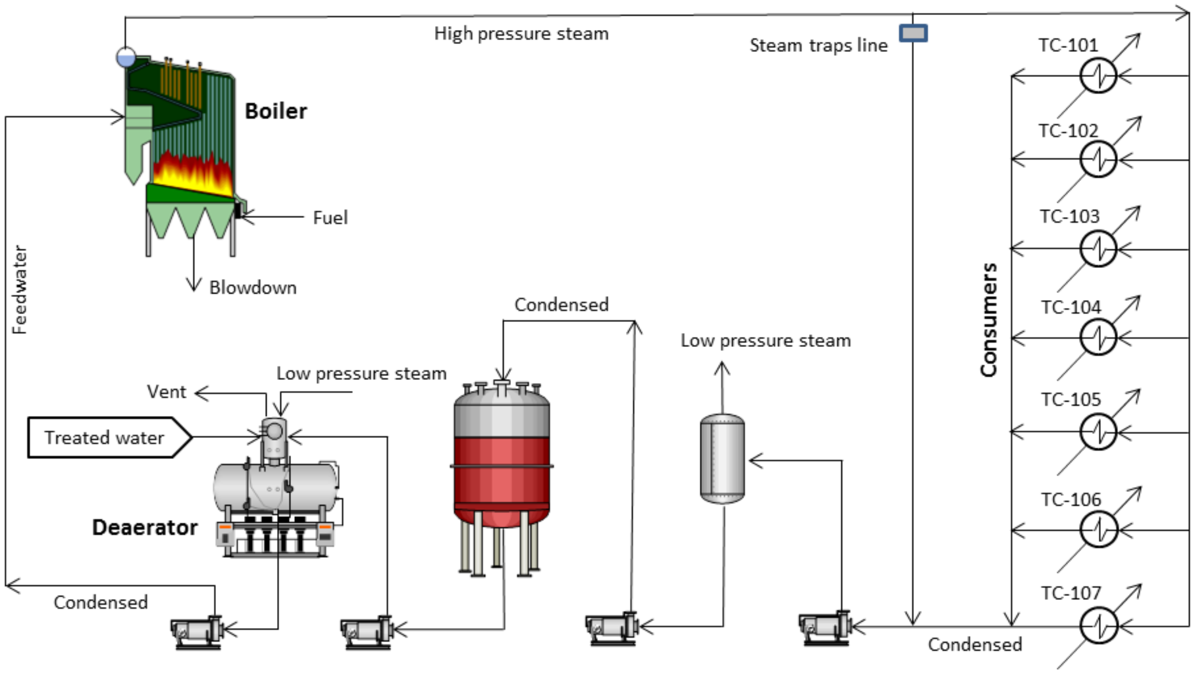

Figure 1. Simplified diagram of a steam distribution system.

3.1 Premises established

- Steam velocity criterion = ≤ 35 m/s;
- Load loss to 100 m of piping = ≤ 0.5 kgf/cm²;
- Steam traps deployed every 50 m of piping;
- Steam traps efficiency of 100%;
- Thermal insulation = rockwool;
- Favorable inclination to flow = 1% of the length of the piping;
- Environment temperature = 30 °C;
- Environment air speed = 1 m/s.

4. RESULTS

This work will be presented four different scenarios of a steam distribution system in order to compare them, validating the practices for energy efficiency increase. Table 2 shows the possible considerations adopted for each scenario. Note that scenarios 1 and 2 have the use of only a nominal diameter pipe, disregarding the speed assumptions and load loss. Already the scenarios 3 and 4, the considerations of speed assumptions and pressure loss, it becomes necessary to change the nominal diameter during the length of tubing. The minimum diameter of 8" initially adopted in all scenarios, was taking into account the economic and operational feasibility. The loss of load and speed in a pipe can be calculated from Eq. (5) and Eq. (6), respectively.

$$\Delta P = 0{,}029\,\frac{\dot{m}^{1.95}\cdot \upsilon^{0.95}}{D^{5.1}} \tag{5}$$

$$v = \frac{\dot{Q}}{A} \tag{6}$$

$$A = \frac{\pi \cdot D^2}{4} \tag{7}$$

Where,
ΔP = load loss (kgf/cm²)
m = mass flow (kg/s)
υ = specific volume of the steam at the operating pressure (m³/kg)
Q = volumetric flow (m³/s)
v = fluid velocity (m/s)
A = cross pipe area (m²)
D = internal pipe diameter (m)

Table 2. Considerations of the scenarios adopted in the simulation.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Nominal diameter 8”	+	+	+	+
Nominal diameter 10”	-	-	+	+
Thermal insulation	-	+	-	+
Steam trap	-	+	-	+

+ (applied); - (not applied)

In the process simulator, the pre-established requirements were inserted, mass flow 67.000 kg/h of superheated steam supplied by a boiler, which will need to travel a distance of 2 km and reach out to their consumers at a temperature of saturation 240 °C, 33 kgf/cm² pressure and flow rates shown in Tab. 1. From the simulations were obtained energy quantities necessary to consumers in the required conditions, and for comparison, the temperature was selected as a parameter to be discussed between the scenarios, due to its direct relationship with the power supply and loss by the system. Table 3 shows the influence of each considerations adopted in the initial temperature for each example. Analyzing the results, note that the scenario 1 was responsible for higher power consumption in the steam generation process, influenced mainly by the absence of the accessories in the steam distribution network. The speed assumptions and pressure loss were not used in scenario 1 and 2 to check the impact on the installation of steam distribution system without the development of engineering projects. With this attitude, it could also notice an increase in energy losses in the system, impacting the power supplied by the boiler and consequently in operating fuel costs, evidenced in Tab. 4.

The scenario 2, with the introduction of accessories (thermal insulation and steam traps) in the vapor line showed an improvement by reducing the initial temperature of the steam hence fuel expense. However, scenario 3, the accessories when removed, only by modifying the nominal diameter of the pipe, it is noted that the initial temperature rose again. This event demonstrates the importance and influence of accessories on increasing energy efficiency in steam distribution system. Comparing scenarios 1 (unmodified) and 3 (without accessories, but with modifications in diameter) is also noticed an influence on the initial temperature, because the increasing the nominal diameter of a pipe, reduces fluid velocity and consequently the load and energy losses caused by reduction speed and friction of the fluid in the pipe walls (Bird et al., 2004). According Sarco (2005), reducing the velocity of the fluid caused by the increase in nominal pipe diameter also reduces the potential for drag condensate present on the line, facilitating its drainage and reducing the problems caused by even in the distribution system steam. The interference in the initial temperature from changes in the nominal diameter is not as intense as the increment of accessories, however, is a parameter which has influence on the energy consumption, both in the boiler as in pressure lifting equipment, since unsuitable diameters can cause high losses of charge and energy in the piping.

Already the scenario 4, it was more efficient, requiring a smaller quantity of energy initially to achieve the predetermined final conditions. This scenario shows importance of using such accessories together with the piping projection, to combat the wastes of energy and mass in steam systems.

Table 3. Initial and final conditions of temperature.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
$T_{initial}$ (°C)	299	269.4	278.5	259
T_{final} (°C)	240	240	240	240
Energy supplied (GJ/h)	174.98	168.52	170.67	166.10

Taking the scenario 4 as a reference and using Eq. (8) to calculate the fuel costs, consumption results were obtained from the scenarios, all shown in Tab. 4 and graphically in Fig. 2. Note that the scenarios that consumed more energy to achieve the pre-established conditions and had higher fuel expenses, do not used the accessories, impacting negatively on the company's economic and environmental issues, increasing emissions of GHGs. In accordance with Fig. 3, the influence of equipment (thermal insulation and steam traps) in fuel economy in this case study was 65.38%.

$$V = \frac{Q}{PCI} \tag{8}$$

Where,
V = fuel volume consumed (m³/h)
Q = amount of energy supplied to the process (kJ/h)
PCI = power lower calorific fuel (kJ/m³)

Table 4. Cost ratio with fuel.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Energy to achieve the consumption patterns (GJ/h)	174.98	168.52	170.67	166.10
Fuel consumption (m³/h)	4916.85	4735.33	4795.74	4667.33
Fuel consumption (m³/mês)	3540134.54	3409438.07	3452936.12	3360477.47
Monthly gain (R$)	206048.70	56152.91	106040.83	-
Annual gain (R$)	2472584.37	673834.93	1272489.93	-

Natural gas - R$ 1.14/m³; PCI = 35587.8 kJ/m³ (Bahiagás, 2016)

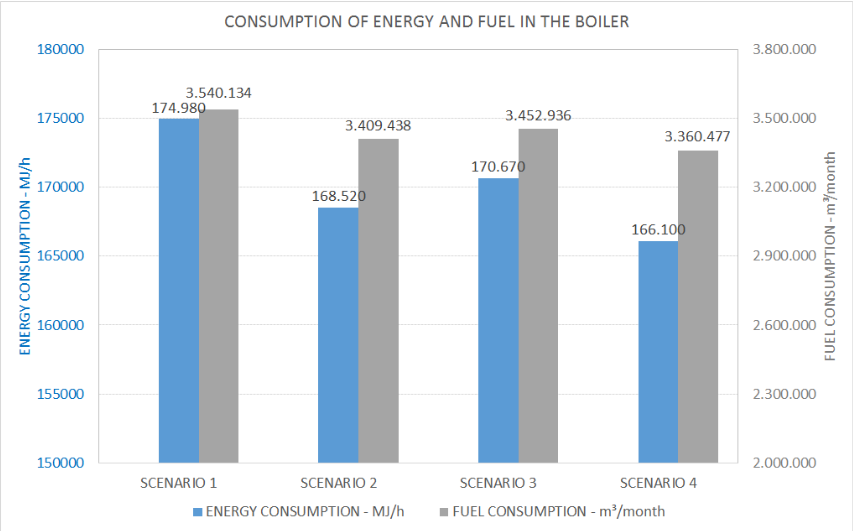

Figure 2. Ratio of energy and fuel consumption in the scenarios.

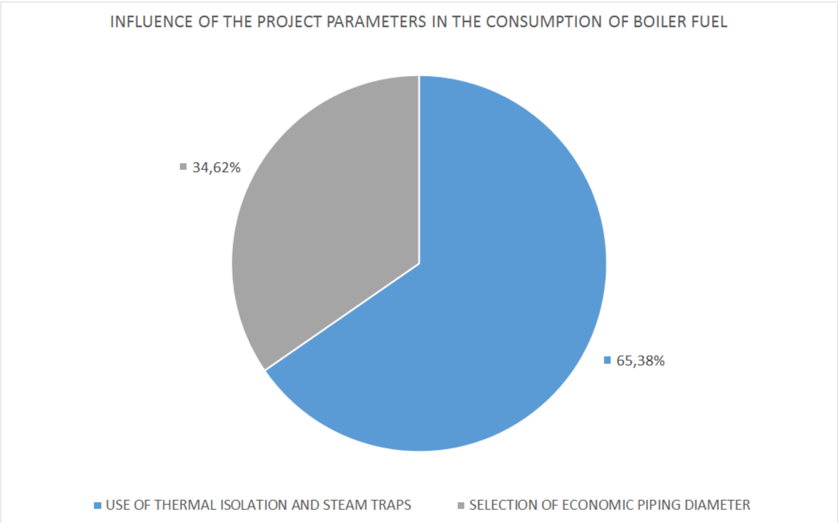

Figure 3. Ratio of the influence of project parameters on fuel consumption.

5. CONCLUSION

Note that the current industrial scenario demands an urgent need for changes in behavior on the way to work with energy in the production and utilities sector. The steam distribution system has not always been a target of major studies regarding the control and energy management to avoid situations that promote the loss of energy and sustainable consumption of natural resources (water and fuel). The way this system is conducted normally, satisfies the amount expectations, but when it comes to quality is observed deficiency, especially in fuel consumption and energy losses to the environment. Steam system projects and maintenance practices and operation are good practices that combat energy waste, capital expenditures, local environmental impacts and promotes the sustainability of the company with low investments.

Some of the concepts of good practice in a steam distribution system were treated in a case study of a utility unit of a company, where the possibilities of fuel costs reductions were addressed through a process simulator and quantified, demonstrating that the use of accessories (thermal insulating and steam traps) in conjunction with the piping project can generate big savings to a company.

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