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HYBRID HEAT PUMPS TO MEET HEATING AND COOLING DEMAND IN BREWERIES AND OTHER PROCESS INDUSTRIES

Rogério Gomes de Oliveira
Universidade Federal de Santa Catarina; Centro de Ciências, Tecnologias e Saúde; Departamento de Energia e Sustentabilidade
rogerio.oliveira@ufsc.br

Abstract. *The feasibility of heat pumps to meet different heating and cooling demand ratios at industries was analyzed through numerical simulation. Heat should be provided above 100 °C, whereas cooling should occur below 0 °C. Eight arrangements were compared and they had the following configurations: (i) and (ii) mechanical compression chiller with electric heater (i) or boiler (ii); (iii) and (iv) absorption chiller and boiler but in arrangement (iv) absorption chiller was also employed as heat pump to meet the heating demand; (v) to (viii) hybrid mechanical compression-absorption machine. Arrangements (v) to (vii) also had a boiler to meet heating demand, whereas arrangement (viii) had an electric heater for such purpose. Arrangements (v) and (vi) had respectively, compressor at low and at high pressures, whereas arrangements (vii) and (viii) had a mechanical compression chiller in cascade with the hybrid machine. Thermal and electrical energy consumption and costs were compared considering boilers fueled either by wood chips or by natural gas. The most efficient arrangement employed an hybrid machine and a boiler. The arrangement with smallest energy cost depended on the fuel employed as main source of thermal energy.*

Keywords: *absorption, ammonia, brewery, heat pump, hybrid.*

1. INTRODUCTION

The brewing process is energy intensive, especially during mashing, wort boiling, wort cooling and fermentation. During mashing and wort boiling, energy is mainly consumed as heat, whereas in wort cooling and fermentation, energy is mainly consumed as electricity. Some microbreweries employ electricity even in heating processes, due to the larger capital cost to acquire a boiler.

According to Galitsky *et al.* (2003), in USA, the electricity utilization in breweries is 2% for boiling, hot water and steam generation, 32 % for process cooling and refrigeration, 46 % for machine drive (pumps, compressors and motors), 7 % for HVAC, 7 % for lighting and 7 for others. Moreover, the Association of Larger Industrial Consumers of Energy (ABRACE), informed that in Brasil, the cost of electricity represents 28 % of the beer price (UOL, 2021).

Scheller *et al.* (2008) informed that the specific consumption in European breweries for electricity and thermal energy are, respectively, between 7.5 and 12 kWh/hL, and between 24 and 40 kWh/hL, whereas Sturm *et al.* (2013) mentioned the study of Felgentraeger and Ricketts (2003) in which they analyzed several breweries with annual production between 1,000 and 10,000,000 hectolites per year and concluded that the electricity consumption ranged from 6.7 to 16.6 kWh/hL and the thermal energy consumption was from 31.7 to 57.1 kWh/hL, with the highest values occurring in smaller breweries.

Alternatives to reduce energy consumption in breweries include the reduction of evaporation during wort boiling, recovering heat from steam produced in wort boiling, using heat storage tanks, adding adequate thermal insulation to equipment and production lines, employing variable speed motors, among other measures (Sturm *et al.*, 2013).

Another way to reduce energy consumption in processes that demand both heating and cooling is through the utilization of heat pump to attend the heating load or to attend both the heating and the cooling loads.

Not only in breweries, but in several food and process industries, products need to be heated and then, cooled, and the combination of cooling and heating power from a single energy input can be one of the major benefits of heat pumps. Instead of having a chiller with a coefficient of performance (COP) of 4 and a gas boiler with efficiency of 80 % (giving an energy utilization ratio of 1.33 for equal cooling and heating power), with combined heating and cooling power production is possible to achieve an overall energy utilization efficiency between 5 and 10 (Hoffmann, 2017).

Commercially available heat pumps using ammonia as refrigerant in mechanical compression systems can produce cooling effect at 0 °C, and deliver heat at 60 °C with COP around 3,5 and coefficient of amplification (COA) of 4,5 (ECT, 2012). However, useful heating at higher temperatures with mechanical compression heat pumps employing ammonia are limited by the high condensation pressure and discharge temperature as most of the compressors are limited to operate with pressures between 2.5 MPa and 3.0 MPa. Even with recent development in ammonia compressor technology enabling discharge pressures up to 60 bar (Bamigbetan *et al.,* 2017), the discharge temperature still would be an issue for simultaneous heating and cooling power production. For example, in a system with evaporation temperature of 0 °C, the discharge temperature of an isoentropic compressor in single stage is 220 °C, which exceeds the maximum operation temperatures for lubricants and ammonia, as informed by Stene (2008) based in the information presented elsewhere (Stene, 1998).

An alternative to overcome the operation conditions limitations of mechanical compression heat pumps is the utilization of hybrid mechanical-absorption heat pumps. They may operate under the Osenbrück cycle, which was patented more than a hundred year ago (Wersland et al., 2017). The hybrid cycle differs from the standard mechanical compression cycle due to the use of a binary working fluid, and by combining the advantages of high COP of the latter cycle with the advantage of high temperature lifts of the absorption cycles. The scheme of the basic control volumes for an Osenbrück cycle is shown in Figure 1.

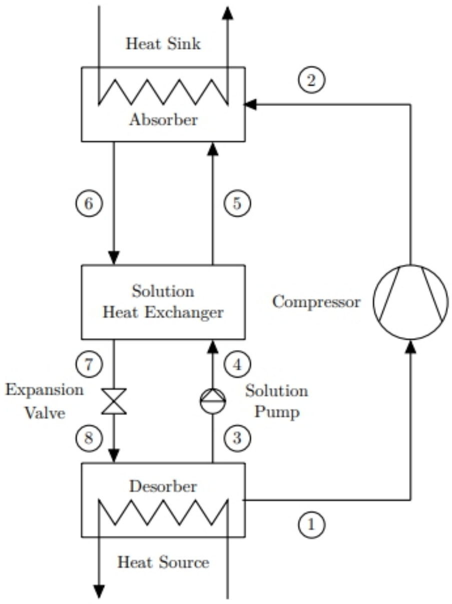

Figure 1. Osenbrück cycle control volumes (Nordtvedt,2005).

Hence, this work presents the results of a study to access through numerical simulation, the feasibility of different equipment arrangements combining heat pumps with boiler or with electric heater to satisfy the heating and cooling demand at different ratios of industrial processes that need heating power above 100 ºC and cooling power below 0°C. The arrangements included absorption heat pumps, mechanical compression chiller and hybrid heat pumps. The hybrid heat pumps operated under variations the Osenbrück cycle and in cascade cycle.

2. MATERIALS AND METHODS

Eight different equipment arrangements were simulated and analyzed to access their energy utilization ratio (overall efficiency) and energy consumption cost per unit of cooling demanded. The equipment arrangements are summarized in Table 1.

Only the energy consumption of main equipment was calculated; hence, the electricity consumed by auxiliary pumps, fans and other accessories was neglected. For the arrangements that employed boiler, the fuel was either wood chips with 30 % dry basis humidity and LHV calculated as 3.15 MWh/ton or natural gas (NG) with LHV equal to 10.9 kWh/Nm³. The mean price in Santa Catarina for wood chips was assumed as R$145/ton, which combined with its LHV results in R$0.046/kWh. The prince of the NG was considered to vary linearly from R$4.51/Nm³ to R$3.84/Nm³ as the monthly consume increases from 300 Nm³ to 2,100 Nm³ (SCGAS, 2021), and the price assumed in the analysis was R$3.84/Nm³. Combing the LHV of NG with its price results in a specific price of R$0.351/kWh.

The boiler fueled by wood chips was assumed to have efficiency of 80 % whereas the boiler fueled by NG was assumed to have efficiency of 90 % (Alfa laval, 2021).

The electricity specific price with taxes for B3 type consumer was assumed R$0.718/kWh (CELESC, 2021). Such a specific price is valid for off-peak utilization. Considering the previously mentioned specific prices for thermal energy and electricity, the ratio between electricity specific price and thermal energy specific price from wood chips and NG is, respectively, 15.6 and 2.05.

In order to evaluate the influence of the fuel and electricity price on energy costs, it was included in the analysis, a scenario where the ratio between electricity specific price and thermal energy specific price (El$/Th$) were 1.0, 1.5, 2.0, and 2.5, and the boiler efficiency was assumed 85 %.

Table 1. Equipment arrangements and their main energy sources.

Code	Combined cooling and heating	Cooling power equipment	Heating power equipment	Main energy source
N_MC+EH	No	Mechanical compression chiller	Electric heater	Electricity
N_MC+B	No	Mechanical compression chiller	Boiler	Electricity and wood chips or NG
N_AB+B	No	Absorption chiller	Boiler	Wood chips or NG
Y_AB+B	Yes	Absorption chiller	Absorption chiller+Boiler	Wood chips or NG
Y_HH+B	Yes	Hybrid Absorption chiller with mechanical compressor at high pressure	Hybrid Absorption chiller with mechanical compressor at high pressure+ boiler	Electricity and wood chips or NG
Y_HL+B	Yes	Hybrid absorption chiller with mechanical compression at low pressure	Hybrid absorption chiller with mechanical compression at low pressure+ boiler	Electricity and wood chips or NG
Y_HC+B	Yes	Hybrid Absorption chiller with two mechanical compressors in cascade with mechanical compression chiller	Hybrid Absorption chiller with two mechanical compressors in cascade with mechanical compression chiller+boiler	Electricity and wood chips or NG for certain heating to cooling demand ratios.
Y_HC+EH	Yes	Hybrid Absorption chiller with two mechanical compressors in cascade with mechanical compression chiller	Hybrid Absorption chiller with two mechanical compressors in cascade with mechanical compression chiller+electric heater	Electricity

The performance indicator (energy utilization ratio and energy consumption cost) for the arrangements that produced both heating and cooling power were obtained at their standard ratio of heating to cooling power production. Moreover, for all arrangements, the performance indicators were obtained for different ratios of heating to cooling demands.

The heating to cooling demand ratio in breweries is estimated to be within 0.6 to 7.6 if one consider the following information:

- specific electricity and thermal energy consumption in breweries are, respectively, between 6.7 and 16.6 kWh/hL, and between 31.7 to 57.1 kWh/hL (Felgentraeger and Ricketts, 2003 apud Sturm *et al.* 2013);
- wort production represents 36% of total thermal energy consumption (Schelle *et al.,* 2008);
- process cooling and refrigeration consumes 32 % of electricity (Galitsky *et al.* 2003).
- overall efficiency of cooling and refrigeration systems is between 0.7 and 7.0 (Thornton *et al*. 2008).

2.1 Mathematical model for the heat pumps

The mathematical model for the absorption machine, combined or not with mechanical compression, was based in the heat and mass balances equations presented elsewhere (Herold *et al.*, 1996), whereas the ammonia-water thermodynamic properties were taken from Ibrahim and Klein (1993). The thermodynamic properties of pure ammonia were taken from Tillner-Roth *et al*. (1993). The equations were solved in the software Engineering Equation Solver (EES).

In all equipment arrangements that employed mechanical compression, the maximum allowed discharge temperature and working pressure was, respectively, 160 °C and 2.6 MPa. The mechanical and the electrical efficiencies were assumed 90 % and the isentropic efficiency (η_s) was calculated with Eq. (1) (Nordtvedt,2005),

$$\eta s = 0.9051 - 0.0422 \times PR \tag{1}$$

where *PR* is the pressure ratio.

For the arrangements that employed mechanical compression chiller as cooling power equipment, the following assumptions were made:

- the evaporation temperature was -5 °C;
- the condensation temperature was 35 °C;
- no subcooling at the condenser outlet;
- negligible pressure drops due to friction;
- superheating at evaporator outlet equal to 5 K.

In all equipment arrangements that employed absorption chiller as cooling power equipment, the following assumptions were made:

- solution heat exchangers had effectiveness equal to 80 %;
- negligible heat losses to the surroundings;
- negligible pressure drops due to friction;
- no subcooling at condenser outlet;
- vapour and liquid were in equilibrium inside the generator and the absorber;
- strong solution leaving the absorber was saturated;
- weak solution leaving the generator was saturated;
- mixing of weak solution and vapour at the absorber inlet was adiabatic;
- evaporator pressure was 300 kPa;
- condenser pressure was 1,350 kPa;
- ammonia concentration at the rectifier outlet depended on the rectifier heat sink temperature, which was 35 °C;
- logarithm mean temperature in the evaporator was 5 K, for cooling in an ambient at 0°C;
- minimum absorber temperature was 35 °C.

The above mention assumptions were also utilized when the absorption chiller was employed as a heating power equipment. In the latter arrangement it was also assumed that the heat released by the absorber should be higher than 100 °C, which in the present study, led to a minimum absorber temperature of 104 ºC and maximum temperature of 114 ºC.

In the arrangement that employed absorption chiller and no compressor, when there was only cooling power production (N_AB+B), the maximum temperature in the generator was 100 ºC, whereas in the arrangement with heating and cooling power production (Y_AB+B), the maximum temperature in the generator was 175 °C. In both cases, there was a 10 K temperature glide in the generator.

In all equipment arrangements that employed hybrid configuration without cascade, the pressure levels were chosen after parametric analysis indicates which levels where capable to maximize energy utilization while meeting the following requirements:

- the vapor stream leaving the rectifier should have the highest ammonia concentration to minimize temperature glide in the evaporator but heat rejection from the rectifier should occur to a sink at 35 ºC;
- cooling power should occur with logarithm mean temperature in the evaporator in the range of 5 to 6 K, while cooling an ambient at 0°C;
- heating power should occur above 100 °C, with minimum and maximum temperature in the absorber, respectively, equal to 105 °C and 115 °C;

The main control volumes for the arrangements with hybrid configuration are schematically represented in Figure 2. For the hybrid cycle with compressor at high pressure (Figure 2a), the pressure levels were 190 kPa, 1,000 kPa and 1,350 kPa, whereas in the cycle with at low pressure (Figure 2b), the pressure levels were 340 kPa, 600 kPa and 1,350 kPa.

In all arrangements that included boiler, it was assumed that the amount of heat supplied to the absorption chiller or to meet a heating demand was equal to the product of the fuel LHV and the boiler efficiency.

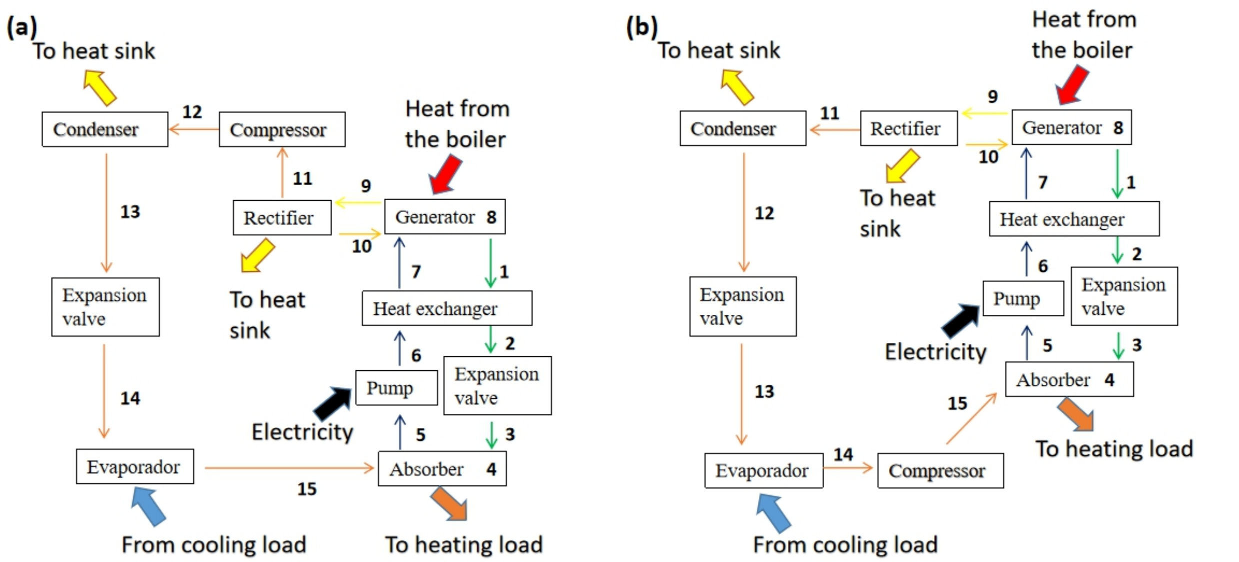

Figure 2. Scheme with the main control volumes for the hybrid cycle. (a) mechanical compression to high pressure. (b) mechanical compression from low pressure.

The main control volumes of the hybrid configurations that employed mechanical compression chiller in cascade is shown schematically in Figure 3. The hybrid configuration with mechanical compression chiller in cascade had the evaporation temperature of -5 °C and the condensation temperature should occur at a temperature higher enough to drive the generator of the hybrid system. For this condition, the condensation temperature was 44 °C whereas the maximum generator temperature was 39 °C with 10 K temperature glide.

With the exception of arrangements Y_HC+B and Y_HC+EH, all other arrangements need an external heat source. However, as can be seen in Figure 3, for the latter types of arrangements, the external heating source is only necessary when the heat released by the hybrid machine cannot meet the heating demand of a process.

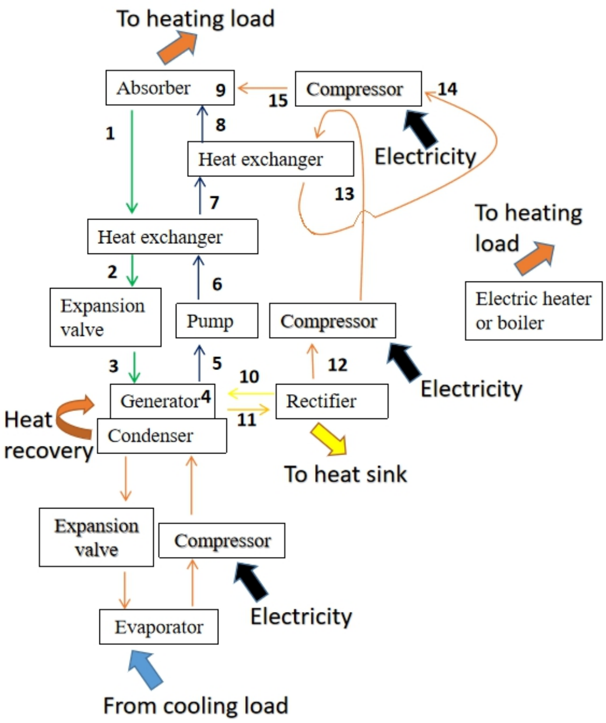

Figure 3. Scheme with the main control volumes for the hybrid cycle with mechanical compression chiller in cascade.

3. RESULTS AND DISCUSSION

For the arrangements with combined production of heating and cooling power, the ratio of heating to cooling power production (H_p/C_p) and energy utilization ratio (ε) is shown in Table 2. Hence, whenever an industry have its demand for heating and cooling equal to ratio of heating to cooling power production of these arrangements, no extra heat source is necessary. However, in the arrangements with boiler(+B), an external heat source would still be necessary, as thermal energy is the main energy input. As for the hybrid arrangement in cascade (Y_HC+), the electricity would be employed only to drive the compressor, as the heat rejected by the absorber would be enough the attend the heating demand. Hence, for this arrangement, there is no difference if there is a boiler or an electric heater as an extra heat source.

Table 2. Ratio of heating to cooling power production and overall energy utilization efficiency for the arrangements with combined heating and cooling power production.

	Y_AB+B	Y_HH+B	Y_HL+B	Y_HC+(B or EH)
H_p/C_p	2.7	3.02	2.11	3.06
ε (wood chips)(1)	0.56	0.32	0.79	2.70
ε (NG)(2)	0.63	0.36	0.89	2.70

(1)Boiler efficiency of 80 %, (2)Boiler efficiency of 90 % (Alfa laval, 2021).

The arrangements with combined production of heating and cooling power could be employed to satisfy the heating and cooling demand in breweries and other industries, if the heating to cooling demand ratio is up to 3.

However, for industries with ratio of heating to cooling demand higher than the heating to cooling power production, the energy utilization ratio varied as can be seen in Figure 4.

The hybrid arrangements in cascade (Y_HC+) are the ones with the highest energy utilization ratio, and not only because their internal heat recovery, but also because electricity is the main source of energy. However, as the heating to cooling demand ratio increases above the heating to cooling power production ratio, their energy utilization ratio decreases as more energy from an external heating source with lower efficiency is needed to meet the heating demand.

For the arrangements with mechanical compression chiller for cooling power (N_MC), and boiler (+B) or electric heater (+EH) for heating power, the energy utilization ratio also decreases with the heating to cooling demand ratio because more energy is consumed by the least efficient equipment.

It is also possible to realize through the combined information of Table 2 and Figure 4, that for the hybrid arrangement with compressor at low pressure (Y-HL+B), the energy utilization ratio is practically constant because the overall efficiency of the hybrid equipment is similar to the boiler efficiency.

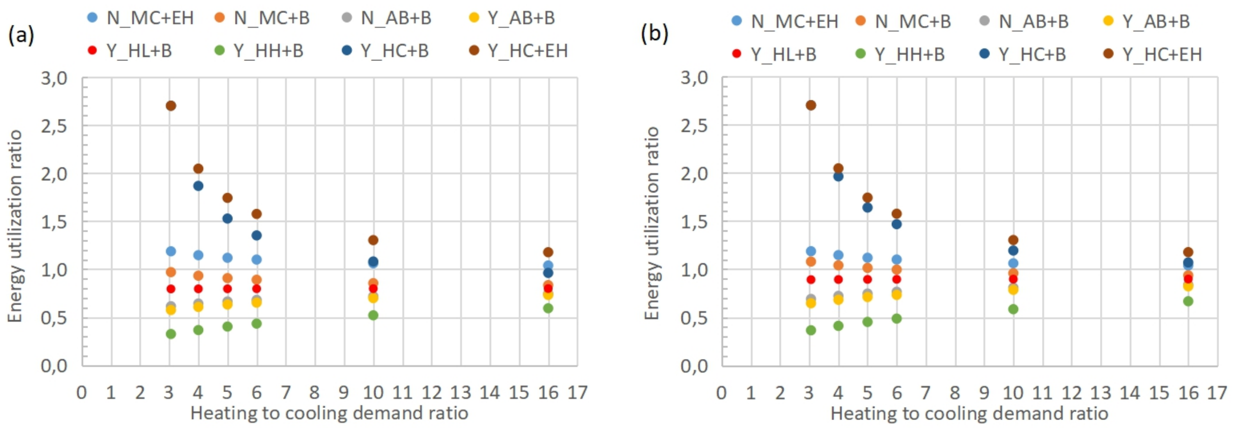

Figure 4. Energy utilization ratio vs. heating to cooling demand ratio. (a) Boiler fueled by wood chips. (b) Boiler fueled by natural gas.

When the price of energy is included in the analysis, it is possible to realize from the information presented in Figures 4 and 5 that although the use of electricity as the main source of energy leads to higher energy utilization ratio, it does not lead to the smallest energy costs, regardless the heating to cooling demand ratio.

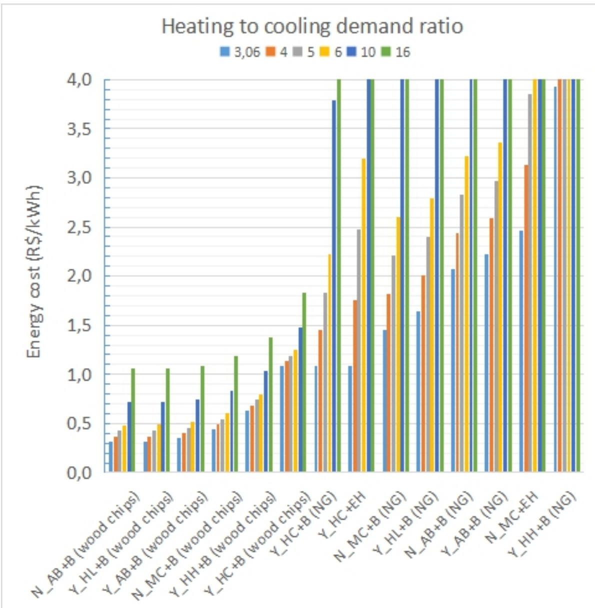

Figure 5. Energy cost per kWh of cooling demand for each arrangement under different heating to cooling demand ratio.

In Table 3 is show the percentual increase of the energy cost, when compared to energy cost of the arrangement with absorption chiller and boiler (N_AB+B) fueled by wood chips, under different heating to cooling demand ratio (H_d/C_d). The energy cost of latter arrangement was chose as baseline because it was the one with the smallest energy cost. The hybrid arrangement with compressor at low pressure(Y_HL+B) and boiler fueled with wood chips had similar total energy cost to that of the latter arrangement, although their electricity and thermal energy cost differed.

Table 3. Percentual increase of energy cost of different arrangements fueled by natural gas or electricity as main energy source when compared to the energy cost of the arrangement with absorption chiller and wood chips fueled boiler.

H_d/C_d	Y_HC+B (%)	Y_HC+EH (%)	N_MC+B (%)	Y_HL+B (%)	N_AB+B (%)	Y_AB+B (%)	N_MC+EH (%)	Y_HH+B (%)
3,06	242	242	360	420	554	601	678	1,141
4	291	374	392	443	558	598	746	1,059
5	329	478	417	461	561	595	800	994
6	359	558	436	475	563	593	841	945
10	429	747	482	508	568	588	940	827
16	478	878	513	531	571	585	1,007	746

In order to evaluate the impact of the fuel prices on the energy cost of the studied arrangements, the comparison of the different arrangements considered a situation in which the ratio between electricity specific price and thermal energy specific price (El$/Th$) were 1.0, 1.5 2.0 (as occurs with the actual natural gas price for monthly consumption equal 2,100 Nm³) and 2.5. For most of fuels employed in boilers, this ratio is within the range 1,5 to 2,5, with exception being when the fuel is biomass, in which this ratio may reach values close to 15, as occurred in the present study.

The energy cost for a heating to cooling demand ratio (H_d/C_d) equal to 3 of the the different arrangements were organized from the smallest to highest following left to right in Table 4. When H_d/C_d is equal to 3, the hybrid arrangement in cascade can provide all heating power necessary to meet the heating demand, hence no boiler or electric heater is necessary, and electricity is the only source of energy.

In most scenarios the hybrid arrangement in cascade was the one with the smallest energy cost, followed by the arrangement with mechanical compression chiller and boiler.

Table 4. Arrangements with smaller energy costs at the heating to cooling demand ratio of 3 under different electricity to thermal energy price per kWh. Smallest energy cost (1º) to the highest energy cost (7º).

	Position						
(El$/Th$)	1°	2°	3°	4°	5°	6°	7°
1.0	Y_HC+(B or EH)	N_MC+EH	N_MC+B	Y_HL+B	N_AB+B	Y_AB+B	Y_HH+B
1.5	Y_HC+(B or EH)	N_MC+B	Y_HL+B	N_MC+EH	N_AB+B	Y_AB+B	Y_HH+B
2.0	Y_HC+(B or EH)	N_MC+B	Y_HL+B	N_AB+B	Y_AB+B	N_MC+EH	Y_HH+B
2.5	Y_HC+(B or EH)	N_MC+B	Y_HL+B	N_AB+B	Y_AB+B	N_MC+EH	Y_HH+B

If H_d/C_d is higher than 3, and El$/Th$ is equal or above 1.5, hybrid arrangement in cascade and boiler have energy cost smaller than the hybrid arrangement in cascade and electric heater. To exemplify the influence of the heating to cooling demand ratio on the energy cost, the percentual increment in the energy cost of the arrangement N_MC+B in relation to Y_HC+B arrangement, at different El$/Th$ and H_d/C_d is shown in Figure 6.

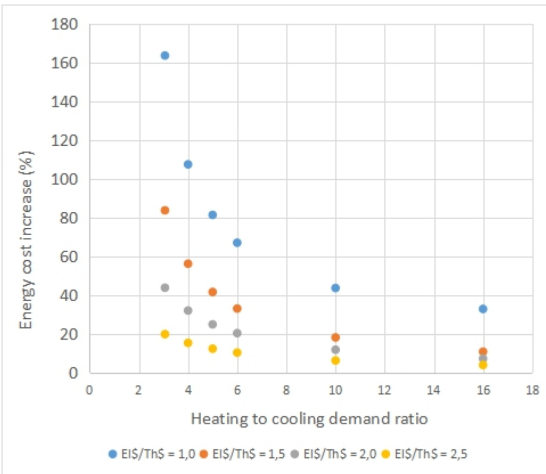

Figure 6. Percentual increment in the energy cost of the arrangement N_MC+B in comparison to the arrangement Y_HC+B.

As can be seen in Figure 6, for the same heating to cooling demand ratio, the percentual difference in energy cost between the two arrangements decreases with the reduction of the boiler fuel price. Hence, considering the complexity and investment capital in the hybrid system, its utilization is more favorable, when the price ratio between electricity to thermal energy is smaller than 2.0 and most of the heating to cooling demand can be satisfied by the heat released by the hybrid equipment.

4. CONCLUSION

The energy utilization ratio and energy consumption cost per unit of cooling demanded of 8 different arrangements aimed to attend different ratios of heating and cooling demand in brewery and other process industries were analyzed.

The arrangements with combined production of heating and cooling power could be employed to satisfy the heating and cooling demand without extra source of heat when the heating to cooling demand ratio is between 2.11 and 3.06.

The hybrid configuration in cascade with a mechanical compression chiller is the arrangement with the highest energy utilization ratio; however, it is not the one with the lowest energy cost if the price of thermal energy per kWh is much lower than the price of electricity, as occurred in this study, in which wood chips was assumed as fuel for the boiler.

Considering heating to cooling demand ratio of 3, which can be found in some breweries, the arrangement with mechanical compression chiller and boiler fueled by wood chips is the one with the smallest energy cost. However, when thermal energy originates from natural gas or other fuels with price per kWh closer to the electricity price, the hybrid configuration in cascade was the one with smallest energy cost.

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