MATEC Web of Conferences **112**, 10001 (2017) DOI: 10.1051/matecconf/201711210001
IManE&E 2017

Energy evaluation at a winery: a case study at a Portuguese producer

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Abstract. The introduction of cooling systems in the wine industry to control the fermentation has allowed the oenologist to produce more and more excellent wines. In this regard, the alcoholic fermentation is a target for various studies that aims at explaining the chemical reactions involved in the release of energy. The aim of this paper is to evaluate the energy consumption of a winery and to discuss and understand the main parameters involved in the process of fermentation. The weather profile during fermentation and the schedule of charging the tanks with freshly affect strongly the needs of cooling power, and the energy use. The study conducted at the Adega da Ervideira in the South of Portugal allowed to define a model for the computation of the cooling power and the electricity consumption. The heat gains from outdoor in convection mode and the heat released during maturation and fermentation phases are the main contributors for the cooling requirements at a winery. As a result of the real fact study, it will allow an oenologist to estimate the cooling power and energy for a winery as well as to produce other types of wines.

1 Introduction

In the last thirty years the wine production changed from an empirical activity to a scientific based approach, what made possible to increase the quality of the wine produced. Many factors interfere in the production of the wine, which need to be taken into account in order to get a wine with a certain quality. The quality of a wine starts on the vineyards, depending on the type of soil, on the solar exposition, on the watering and on the care activities especially in what concerns to the grapes.

After the growing process, the oenologist needs to define the date to harvest the grapes checking the maturity of the grapes. The process of harvesting may be mechanical or human based, depending on availability of resources or on the quality of grape required for special wines. Special attention needs to be taken into account regarding the transportation, in order to avoid a preliminary fermentation. Many producers tend to transport the grapes in refrigerated vans and harvest the grapes during the night to maintain the bunches at

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temperatures lower than 20 °C.

Thus, inside the winery the collected grapes undergo a process of maceration that allows creating the must. The must may be filtered, and sometimes undergoes centrifugation or flotation processes to get rid of solid parts, activities usual in the production of white wines. In this phase, the oenologist may ask to correct the acidity and the sugar content of the must. Next, the must is transferred to large wine tanks, where the fermentation takes place at precise temperatures according to the type of wine. During this phase most of the ethanol is produced.

The maturation process allows warranty the stability of the wine colour and the reduction of the astringency of the wine. This phase develops in oak barrels or stainless steel vats during a period of time that varies from six months to two years. The maturation continues in bottles, a process that should occur at a stabilized temperature. All of these activities interfere in the organoleptic characteristics of a wine, allowing to define the flavour, the astringency, the colour, the acidity and the aromatics of a wine.

The aim of this paper is to establish the energy balance of a winery, allowing to define the energy needed to run it. Most of the energy needed comes from the cooling process, which is responsible for about 54% of the energy use of the winery. Therefore, changing the fermentation temperature to alter the organoleptic characteristics impacts the energy use of a winery.

The energy model developed in this study takes into account the energy released during the fermentation process and the transfer of energy between the tanks and the atmosphere. The fermentation process starts by a natural decomposition of the glucose, ending on the formation of ethanol [1]. During the process, energy of circa 550 kJ/kg of glucose is released [2-5] in the fermentation process, which has to be removed from the tanks in order to avoid increasing the temperature of the must. The energy released transfers by natural convection between the must and the atmosphere, making the calculation of energy needed to depend on the local weather condition.

Thus is possible to calculate the cooling power needed in a vineyard, as well as to estimate the energy used in cooling and to evaluate the energy use for different operation conditions. The application to a winery of Ervideira, Alentejo, Portugal shows the value of the model briefly described above.

2 Energy in the fermentation process

The fermentation process was first exposed by Guy-Lussac in the equation of decomposition of glucose $C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$, showing that the reaction produces ethanol and carbon dioxide while releasing energy. Nowadays, the wineries control the starting of the fermentation by introducing yeast in the must after filling the tanks with fresh squeezed must. During the fermentation, the must is usually in contact with solid parts of the grapes, in order to get special organoleptic characteristics developed in the maceration process [6]. Moreover, moving the must avoid the development of bacteria on the surface of the must in contact with the ambient air. The old maned chewing process was able to allow the aforementioned contact, but now a pump moves the must from downwards to upwards of the tank. A similar technology rolls the must in a rotary vat with horizontal axis, allowing the carbon dioxide released to stay in contact with the must, periodically discharged into the ambient [7].

Increasing the temperature of fermentation to the range of 25 °C to 30 °C, being 30 °C the better for the development of the yeast, gives rise to more coloured wine attained by a faster formation of ethanol. The wineries tend to ferment red wines at about 25 °C achieving an almost complete fermentation. For white and rose wines the fermentation is controlled at lower temperatures to get fruity wines by avoiding the evaporation of aromatics [8].

The production of the glucose in the grapes starts in the photosynthesis process, an oxi-reduction process that allows the energy from sunlight to supply the ADP (adenosine diphosphate) and other phosphate molecules. These molecules thus form ATP (adenosine triphosphate) and NADPH (Adenine Nicotinamide Dinucleotide), used to produce glucose, a second product of photosynthesis [1].

During the fermentation process, the yeasts allow producing alcohol and carbon dioxide from the glucose in an exothermic process. Glycolysis is the set of reactions that degrade glucose in pyruvic acid, or pyruvate, latter reduced in a set of reactions leading to produce alcohol and carbon dioxide.

The reduction of pyruvate or pyruvic acid ($C_3H_4O_3$) is anaerobic, done by the action of NADH formed during glycolysis. The pyruvate give origin to Acetaldehyde (C_2OH_4) and later reacting with the molecules of NADH generates ethanol (C_2OH_6) [1,2].

S. Yonsel et al. range the enthalpy released in the decomposition of glucose from -450 to -550 kJ/kg, a value similar to the one attained by Dubrunfaut in 1856 who stated a value of -527 kJ/kg [4]. In 1979, Boulton defined it to be -651.28 kJ/kg for broad sugars [5, 9]. Recently in 2005, Von Stockar et al. defined the enthalpy of decomposition of glucose to be -100 MJ/kmol or -555.1 kJ/kg of glucose [10]. The book "2006 ASHRAE-Refrigeration Manual (SI)" presents in the "Beverages" section similar values for the enthalpy of decomposition of glucose, varying between -83.7 to -100.5 MJ/kmol most used to be 99.6 MJ/kmol [11]. Hence, a sugar content of 220 kg/m3 of must decomposed to 98.5% releases an energy per cubic meter of must of 119.2 MJ.

Therefore, estimating the energy of fermentation from a certain quantity of must is a question of knowing the moles of CO_2 released in a steady state process. The set of fermentation reactions changes the glucose to ethanol, a product with about half the density of glucose. El Haloui et al [12] correlated the energy release to CO_2, the CO_2 released to the change of glucose, and the sugar content of the must to the density of the must as well as to the energy released. Based on the aforementioned work, A. López and P. Secanell [13] estimate the rate of heat released during fermentation, from the variation of the density of the must.

Being Z the sugar concentration of the must in g/L, Z_0 an initial sugar concentration, and d the density of the must, A. López and P. Secanell found:

$$Z = 0.99109 \cdot Z_0 - 2096.3 \cdot d + 2078 \tag{1}$$

The rate of energy released, Q [kJ], follow the rate of sugar consumed Z as:

$$\frac{dQ}{dt} = 0.55 \frac{dZ}{dt} \tag{2}$$

And the total energy released from a state Z0 to Z:

$$Q_e = 0.5451 \cdot Z_0 - 1152.97 \cdot d + 1142.9 \tag{3}$$

Equation 3 allows to compute the total energy released until time t, knowing the initial sugar content of the must and the density at time t.

3 Heat Transfer

The Ervideira winery is open to the exterior on the North and East bounds and covered by a non-insulated white metal sheet. The tanks are therefore at atmospheric conditions, subjected to radiation from the cover and to direct radiation from the East area.

Hence, it is necessary to calculate the convection heat-transfer coefficients, inside and outside, of the tanks in order to determine the heat flow at any hour. Inside the tanks the convection is natural convection as well as in the outside of the tanks, due to low wind velocities found in the winery.

In natural convection the convection heat-transfer coefficients is governed by the Grashof number, Gr, that in turn varies with the difference of temperature between the wall temperature and the fluid temperature. The Nusselt number, Nu, allows determine the heat convection coefficient, h, for a characteristic length, x, and fluid thermal conductivity, k. Nu varies with the geometry and with the Rayleigh number, Ra, according to:

$$Nu = \frac{h \cdot x}{k} = C \cdot Ra^{m} \tag{4}$$

In Equation 4, C and m vary with geometry and with the Rayleigh number, this being $Ra = Gr \cdot Pr$, where Pr is the Prandtl number of the fluid slightly dependent on temperature. Therefore, Nusselt number varies mostly with the temperature of the surface.

For each type of surface of tanks and vats, determining the surface temperature involves an iterative method, as the h value varies with temperature. The method starts by determining the convection heat-transfer coefficients based on an estimated surface temperature, thus calculating the heat flux, and then the new surface temperatures. Achieving a new surface temperature a new iteration is performed, until reaching convergence to the value for h. The heat balance needs to determine h for each surface, at each hour of the energy calculation, as the outside temperature varies during the period of wine production.

Figure 1 depicts a vertical and a horizontal tank, showing on the horizontal vat picture the possibility of rolling the vat allowing to transfer the must from the downside to the upside.

Fig. 1. Vertical (left panel) and horizontal (right panel) vats

Using Equation 4 with the appropriate coefficients it is possible to calculate the heat-transfer coefficients from the inside and outside convection on each vat. Figure 2 depicts the type of heat-transfer coefficients computed for each vat.

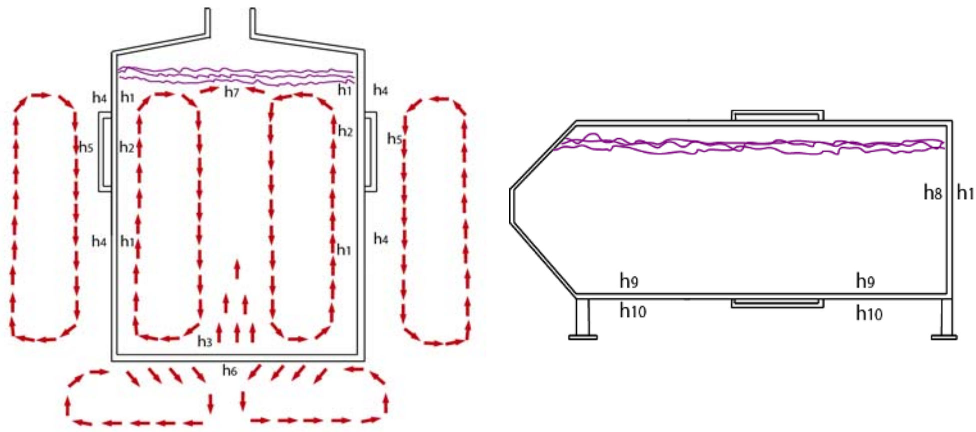


Fig. 2. Heat-transfer coefficients for vertical vats (h1 to h7) and for a horizontal vat (h8 to h11)

The heat-transfer coefficients by convection vary depending on the direction of the heat flux, making it necessary to compute the heat-transfer coefficients when the room temperature is lower and when it is higher than the must temperature. Table 1 shows an exert of the computed heat-transfer coefficients for two vertical (25 CV, 5 CV) and one horizontal (10 V) vat in the situation when room temperature is higher than the must temperature.

Table 1. Convection heat-transfer coefficient [W/m^2·°C] for some VATs for room temperature higher than must temperature

Winery reference of the vat	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11
25 CV	109	118	177	8	19	3					
5 CV	134	139	218	12	12	4	1				
10 V								111	111	4	2

The tanks exchange heat by radiation with the metal sheet that covers the winery and to the East facade of the winery directly opened to outdoors. The direct and diffuse radiation at each hour of the day entering the east façade, Ee, allows determining the solar gains of the tanks nearby. The heat flux gained per square meter is $q = \alpha \cdot E_e$, where α is the absorptivity of the material taken as 0.5.

The metal sheet introduces a radiation shield to the tanks whose temperature is determined based on the heat balance between the solar radiation received by the roof and the convection heat transfer on upper and lower sides of the cover. The temperature of the roof, Tr, allows determining the radiation heat transfer per unit area to each surface of the tank at temperature T_{ti}, after calculating the view factors, F_{i-r}, of the surfaces to the roof, by:

$$q = \alpha \cdot F_{i-r} \cdot \sigma \cdot (T_r^4 - T_{t_i}^4) \tag{5}$$

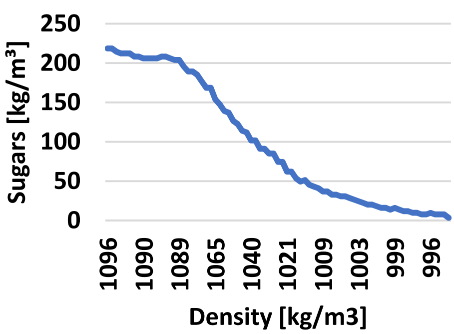
 DOI: 10.1051/matecconf/201711210001

4 Energy Model for Ervideira

The Ervideira winery, located nearby Évora, Portugal, has 160 ha of vineyard and produces about 800.000 bottles of different wines each year. The following study reports to the period of August 11 to October 12, 2015, when data for tank scheduling and energy use was collected. The winery has 30 tanks for wine fermentation with a total volume of 385 m3 and 16 more for wine maturation. The temperature during the maturation phase might not overcome 20 °C, and the fermentation might occur at 25 °C for red wines and at 15 °C for white wines. A refrigeration water network with a central chiller allows removing the heat gained by the tanks due to the chemical process and to the heat transfer. The chiller has 149 kW of refrigerating power, fluid R410a, overall seasonable efficiency of 2.58, with auxiliary pumping system of 2 kW.

The INETI weather data file for Évora, TRY format, have the data for temperature, solar radiation and wind that allows defining the outdoor conditions during the period of wine production. Évora is a hot place during the summer, with design temperature of 35.2 °C at 97.5% of probability of occurrence. Anyway, the average outdoor temperature during the period of fermentation is about 24 °C, having a low impact on the energy introduced in the vats allocated for the fermentation of red wines.

Regarding the data of the must, the winery has daily data for each tank concerning temperature and density of the must. Therefore, Equation 3 allows determining the daily energy removed from each tank, as depicted on Figure 3 (right panel) for a white wine tank. A real tank receives many different charges of maturated must from different types of grapes, making the density to increase anytime a new must is added. Figure 3 depicts a real evolution of sugars against density, for a white grape variety. On the right panel it shows the energy needed to be removed from a white wine tank, calculated by the variation of density, averaged by the red line tendency.



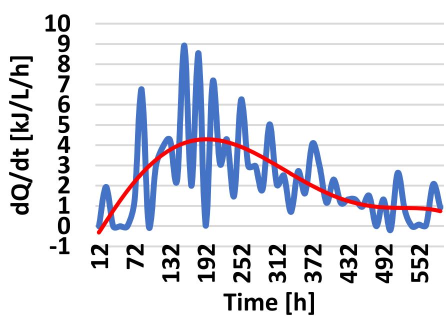


Fig. 3. (left panel) Sugar content and density (data collected daily) for a white grape variety; (right panel) real energy released in a tank due to fermentation and charging

The total heat removed by the chiller from the fermentation tanks is the sum of heat released during fermentation processes and energy transferred by radiation and convection from the environment.

The hourly weather data for Évora and Equation 4 allow determining the hourly convection coefficients for each surface of each tank. Equation 5 allows computing the energy transferred by radiation.

Therefore, knowing the production stage at each vat during the year of 2015 it is possible to calculate the energy transfer by convection and radiation to each vat, and accounting the energy needed to remove in the fermentation process.

Figure 4 depicts the total thermal power transfer into the fermentation tanks during the season of August to October by convections and radiation, not including the fermentation energy. It does not account for the thermal energy of the fermentation process. Anyway, it accounts for the different temperatures of white and red fermentation vats.

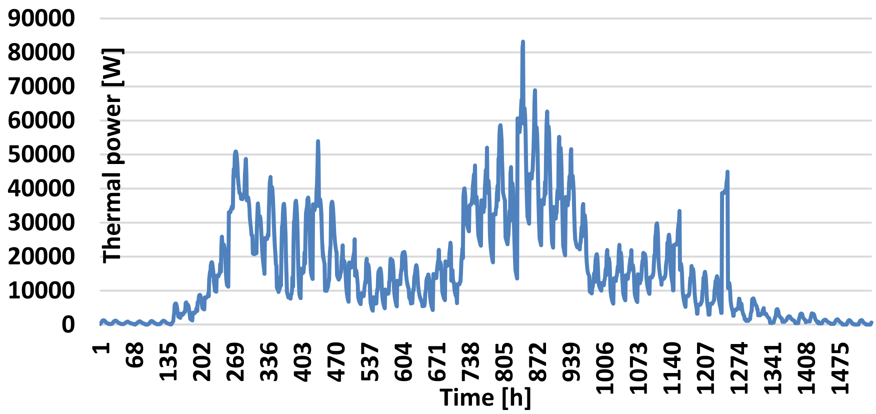


Fig. 4. Total convection and radiation thermal power for all fermentation tanks during the season

In a similar way, Figure 5 shows the thermal energy needed to be removed from all maturation tanks between May and October.

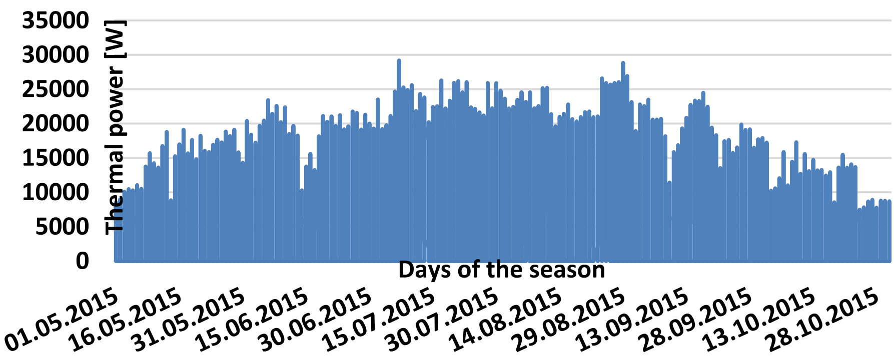


Fig. 5 Total convection and radiation thermal power for all maturation tanks during the season

Accounting the complete season of maturation and fermentation, the energy for maturation is about 77% of the all energy. Concerning the period of about two months when maturation and fermentation happens the total energy for maturation is similar to the one for fermentation tanks. The fermentation of red wines is achieved at a constant temperature of about 25 °C, making the contributions of the heat exchange by radiation and convection to be below 15 %. On the other hand, white wines has lower periods of fermentation at lower temperatures than the red wines, making convection and radiation to attain about 65% of the needs of energy. The effect of radiation accounts for less than 5%.

Figure 6 depicts the complete amount of the thermal energy use during the wine production from May to October 2015. The picture shows in the bottom a white area from 11 August to 12 October regarding the energy for fermentation, and in the top area the thermal energy regarding the convection and radiation. The figure displays a maximum of 136 kW of cooling power, for a maximum production of the chiller installed of 149 kW, being a reference of the quality of the model. During the wine production period the cooling needs are 96.2 MWh, corresponding to about 37.3 MWh of electricity use in the chiller. Considering the pumps, the electricity use is 43.8 MWh, about 54% of the total electricity consumption of the winery, which is within the range of energy consumption for this type of applications [14]. The electricity invoices shows an increase for the same period of 37 MWh, making the model to be in an acceptable margin of error of 15%, common on energy evaluations.

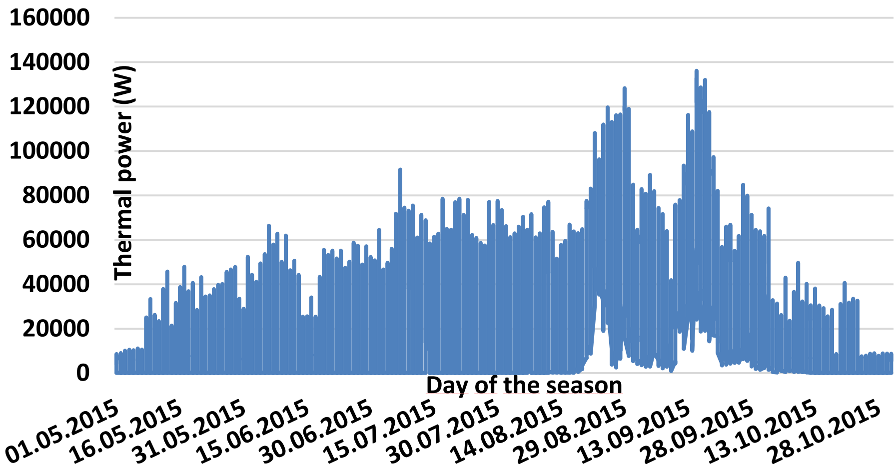


Fig. 6. Total thermal power for all fermentation and maturation tanks including the fermentation power in white.

The model allows testing various improvements in the winery, the best being the insulation of the tanks and the insulation of the metal sheet of the roof. The former allows a reduction of electrical energy use of 18.3 MWh and the roof insulation only 1.1 MWh, both improvements influencing the stability of the temperature in the tanks. Due to the stability of temperature in the tanks, the insulation improvement is more than an energy improvement: it is a quality improvement of the production of wine.

5 Conclusion

The Adega da Ervideira is a winery located near Évora, South of Portugal, producing 800.000 bottles of wine a year. The winery has 46 tanks, 30 of it dedicated to the fermentation process with a total volume of 385 m^3. Évora is a location with hot temperatures during the summer, what makes important to reduce the heat transfer to the tanks.

The electric energy use during the wine production represents about 54% of the annual electricity consumption of the winery. The electricity for wine production totals 43.8 MWh/a, therefore about 5.5 MWh/a per 100.000 bottles.

Regarding the thermal cooling power, the winery needs a maximum cooling power of 136 kW, accomplished by a chiller of 149 kW, or less than 20 kW to produce 100.000 bottles.

In what concerns to improvements in energy, the insulation of the tanks is the most important improvement due to the hot climate of the location. This improvement would reduce the electricity use by about 40% during the wine producing period, or roughly 20% of the electricity paid in a year.

The authors gratefully thank the sponsorship of Fundação para a Ciência e Tecnologia through the Strategic Project UID/EMS/00667/2013 – UNIDEMI.

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