Refrigeration in Winemaking Industry

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Additional information is available at the end of the chapter

Abstract

The effectiveness of winery operations in a wine cellar and their impact on wine quality depend closely on the technology used. A correct application of refrigeration systems is perhaps the best guarantee of a correct processing process. In this work, a review of the refrigeration engineering in warehouse is carried out, calculating the refrigeration needs of each one of the main stages of elaboration, according to the different winemakings. The energy requirements for the cold maceration and debourbage in white winemaking, the cooling of the crushed-grapes in the elaboration of red wine, as well as for the temperature control during fermentation and physical-chemical stabilization of the finished wine are calculated. The main cold production techniques in the winery are also addressed to respond to those needs.

Keywords: winemaking, refrigeration, fermentation, tartaric stabilization, wine refrigeration exchanger

1. Introduction

The temperature control in each one of the winemaking operations is a usual and extended practice. The thermal conditioning of the grapes on their arrival at the winery is already an essential requirement in some wineries, and even the grape harvesting systems are adapted to this factor (early or even night grape harvesting), which is very important in warm regions.

The prefermentation works of cold maceration and debourbage in white winemaking, the pellicular maceration in red wines, the controlled fermentations, as well as the processes of finished wine conditioning require a control and maintenance of their optimum temperatures. **Table 1** shows the most important applications of refrigeration in a warehouse, as well as the optimal temperatures for each operation.

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Importance

Operation	V. in white wine	V. in red wine	Optimum temperature	Effects on wine/must
Cold extraction	+	−	−5/−10°C	Must sugar concentration by elimination of frozen water
Cold maceration	++	++	5/10°C	Extraction of aromatic precursors Fermentation delay
Musts Refrigeration	+++	+++	10/18°C	Enable the debourbage in white wines In red wines lower the temperature until the optimum of fermentation
Deboubarge	+++	−	10/15°C	Accelerate the sedimentation process Delay the start of fermentation
Pellicular maceration	++	++	<15°C	Extraction of polyphenolic fraction and aromatic precursor in red wines before fermentation
Fermentation thermal control	+++	−	13/20°C	Aromatic enhancement in white wines Avoid fermentation stops
Thermal control of fermentation and meccanization	−	+++	25/30°C	Decrease aromatic losses Avoid fermentation losses
Cold storage of finished wines	+++	+++	10/15°C	Slow down microorganisms metabolism Decrease oxidation and aromatic losses
Amicrobic stabilization	+++	++	<5–10°C	Filtration process improvement
Colloidal stabilization	−	+++	<5–10°C	Hasten unstable coloring matter
Tartaric stabilization	+++	+++	−5/1°C	Hasten tartaric salts of calcium and potassium Control the oxidation-reduction process and cession
Aging in oak	+++	+++	15–20°C	Decrease volume losses Avoid undesirable microbial development
Second fermentation in bottle	+++		12/15°C	Control the alcoholic fermentation. Refinement of sparkling wine by slow transfer of fermentation and autolysis products.
Bottling	+	+	15°C	Reduce loss of aroma and enable the process
Bottle store	+++	+++	12–18°C	Enhance wine stability

Table 1. Applications of cold engineering in a wine cellar: optimum working temperatures in wine cellars and the effect on must/wine.

2. Refrigerating necessities on prefermentative operations

The temperature control can be done from the first stages of winemaking, by cooling the freshly squeezed grape or the must at the exit of the press. Most authors recommend the entry

of red wine vintage at 20°C due to an inlet temperature of 26–28°C, this can lead to a difficult start of fermentation and higher production of volatile acidity [1–3]. The prefermentative maceration applied to certain varieties (Pinot Noir) for the extraction of polyphenols needs to bring the crushed-grapes to temperatures below 13°C, to avoid starting fermentation [4].

In white wines, the pellicular maceration of aromatic grapes (Moscatel, Gewürztraminer, Verdejo, Sauvignon Blanc and Chardonnay) at low temperatures enables the extraction of aromatic compounds. The static debourbage is a slow process, which allows in its course the proliferation of microorganisms. Cold helps to stop or slow the start of fermentation, and the low temperatures increase the speed of sedimentation. Time and temperature are the keys for a quality debourbage. The use of pectolytic enzymes allows a considerable reduction of debourbage times, but on the other hand, the cold slows down the enzymatic phenomena of despectination. Therefore, in the debourbages with addition of enzymes, the temperature of the must should not be less than 10°C [5, 6]. The promptness of enzymatic debourbage is doubled when the temperature rises to 10°C, at the expense of risks of grater microbial proliferation, and is discouraged for vintages with poor sanitary quality. Temperatures under 8°C promote the inactivation of the enzymes and lengthen the fermentative latency phase. In any of the above cases, the refrigeration needs to cool the must or the crushed-grapes to the operating conditions are defined by the fundamental equations of the energy balance (Eq. (1)) [3, 7–10]:

$$dQ/dt = m \times C_e \times \Delta t \tag{1}$$

- dQ/dt is the cooling capacity per unit of time (kJ/h).

- m is the mass flow of must or crushed-grapes (kg/h). $m = vx_\rho$.

- ρ is the density (kg/m^3).

- C_e is the specific heat of the must/crushed-grapes/wine, which according to authors is:

    - C_e = 4.18 kJ/kg °C [11,12].

    - C_e = 3.8 kJ/kg °C for musts with a density of 1090 kg/m^3 [13].

    - C_e = 4.5 kJ/kg °C for wines with a density of 995 kg/m^3 [13].

    - C_e = 3.65 kJ/kg °C for musts and 4.15 kJ/kg °C for wine [14, 15].

- Δt is the (initial temperature–final temperature) of must/crushed-grapes.

3. Refrigeration requirements in prefermentative operations

The fermentation of sugar by the yeast glycolytic allows the cells to transform glucose and fructose into pyruvic acid and this, through an enzymatic complex of carboxylase activity, will be transformed into acetaldehyde, which is finally reduced by the alcohol dehydrogenase into ethanol. This transformation is an exergonic reaction, releasing heat which, when accrues in the must, causes a thermic elevation.

The metabolic activity of the yeasts increases in proportion with the temperature with maximum rates between 25 and 28°C [16]. Temperatures above 32–35°C imply high risks of fermentation stops, as well as further proliferation of acetic and lactic bacteria. Fermentations below 18°C are distinguished by delayed onset (longer latency phase) and very slow fermentation development. In years of warm harvests, in large deposits or cellars in the middle of the season with several fermentation tanks, it is easy for the microbial activity itself to pass through the 35°C barrier, negatively affecting both cellular viability and the sensorial characteristics of the wine [1–3, 16, 17]. On the other hand, fermentations at moderate or even low temperature (below 18°C) allow preserving the aromatic precursors of the grape varieties and stimulating the formation of secondary compounds by yeasts. All this underlines the importance of having a temperature control of fermentation in the wine cellar. It is considered suitable for fermentation of red wines 28–30°C (aid to maceration), while for fermentation of white and rose, temperatures below 22°C are recommended. The cooling of the must or the crushed-grapes, as indicated above, allows the fermentation process to start at the desired temperature in the case of warm harvests. It is an added advantage in the case of a cold debourbage.

The low temperature fermentations (13°C or less) have a great interest for the production of white and rose wines, especially for musts arising from varieties with a great aromatic potential. In addition to avoiding their evaporation, the low temperatures considerably condition the bacteria development, allowing the use of less doses of sulfur dioxide.

It does not happen the same with the yeasts. The low temperatures influence in a different way on the different species which concur in the must. Some yeasts such as *Kloeckera apiculata* dominate fermentation at 13°C, according to Heard and Fleet [18]. The survival of non-*Saccharomyces* species affects the production of certain undesirable volatile substances such as acetic acid and ethyl acetate [19]. The temperature affects the biochemical activities of fermentative yeasts, which in turn affects the wine and its composition. The most notable effect of yeast adaptation at low temperatures is the increase in the degree of unsaturation of the fatty acids [20] and the reduction of the synthesis of sterols. Both changes are an important determinant of the membrane fluidity and reduce the transit of nutrients, resulting in an inhibition of fermentative activity.

According to Suárez and Iñigo [1], not all sugar molecules will follow the equation of Gay-Lussac, obtaining two molecules of ethanol and two of CO_2 for each mole of glucose, but depending on the metabolism of the yeast, a certain number of molecules are going to be intended to glycerine and pyruvic acid, which will be the origin of secondary products in wine. As a consequence, the thermal flow originated during fermentation will depend on the importance of these secondary reactions.

Bouffards [21] using a sealed calorimetric chamber determines the heat of fermentation reaction between 83.7 and 100.5 kJ/mol. Subsequently, several authors have established a thermal flow ranking from 71 [22] to 106 kJ/mole [1], according to the purity of the fermentative process and the derivation of the glucose molecules toward other secondary metabolic routes. Assuming the most thermodynamically adverse case and the known parallel reactions always occurring to the alcoholic fermentation, the average mean value of heat flow most widely accepted by the various experts is 100.32 kJ/mole [2, 3, 10, 19, 23].

This heat released by mole of transferred sugar corresponds to the theoretical case of an instant fermentation process. In fact, the process lasts several days in which heat dissipation takes place by contact of the tank walls with the outside and by the release of volatile products released during the transformation. According to this, the data referred to by the authors mentioned above as energy released during the process are modified by a factor corresponding to the rate of consumption of sugars throughout the fermentation process with units of [mole/m^3.h]. This aspect, directly related to the concentration of ethanol and CO_2 produced per unit of time, depends on the physical and chemical conditions of the fermenting must (content in sugars, temperature, acidity, pH and richness in nitrogen sources), operating conditions (yeast morphology population, temperature, agitation and oxygenation) and fermentation time.

To identify and quantify the influence of these factors on the amount of heat energy released throughout the fermentation time, several authors have developed simulations and mathematical models.

Boulton [24] establishes that the loss of heat throughout the fermentation process is defined by Eq. (2):

$$dQ/dt = \Delta H \times dS/dt, \tag{2}$$

- dQ/dt is the energy released per unit of time (kJ/h).

- ΔH is the energy released during fermentation of one glucose mole (kJ/mol).

- dS/dt is the rate of reduction of sugar content by yeast consumption (mol/m^{3}h).

This quantification system of the energy released during the fermentation process is the most widely accepted by the experts, although there is no consensus regarding the calculation and valuation of the term dS/dt, that is, to say on the system of calculation of the decrease in the concentration of fermentable sugars per unit of time. Several authors propose mathematical models to define this rate of degradation, based on empirical data from different variables.

The model proposed by El Haloui et al. [25] relates the concentration of residual sugars with the volume of CO_2 released, according to Eq. (3):

$$S = 3.92 \times V_{CO_2} + 0.1463 \times S_o - 117 \tag{3}$$

where

S is the sugars consumed in a precise moment (g/L).

V_{CO_2} is the volume of CO_2 produced until that moment (L).

S_o is the initial concentration of sugars (g/L).

The volume of CO_2 released can be calculated by empirical analysis in laboratory scale tests with Muller valve occluded flasks [1] or at the level of experimental microvinifications using CO_2 flowmeters [26, 27].

Afterwards, and based on empirical data, the same authors [28] build a model which relates fermentation curve with the density and initial concentration of sugars in the initial must (Eq. (4)):

$$S = 0.99109 \times S_o - 2.096 \times 10^3 \times d_{30°} \text{ relative must density} - \text{wine at } 30°C \qquad (4)$$

The concentration of residual sugars in each moment of the fermentative process can be calculated, establishing the concentration of glucose-fructose by enzymatic methods or by detection systems based on measurements of radiation in that infrared spectrum.

López and Secanell [15] develop a complex model of the heat evolution curve during fermentation based on physical-chemical parameters such as initial sugar content, total acidity, fermentation temperature and duration of this one. They get expressions such as Eq. (5):

$$\mathrm{d}Q/\mathrm{d}t = \frac{k_1}{k_2 - k_1}(e^{-k_2 t} - e^{-k_1 t}) \qquad (5)$$

in which k_1 and k_2 at the same time are constants representing values of activation energy of the fermentative chemical reaction and depend on the temperature and the total acidity of the must. Starting from this equation, the authors calculate the maximum energy evolution during the process according to the following expression (Eq. (6)):

$$Q_{\max} = 100.32/180 \times S_o \times F_c \qquad (6)$$

where

S_o is the initial sugar concentration (g/L).

F_c is the correction factor depending on initial concentrations.

Avilés [11] states that the heat developed in fermentation of the must is determined by the probable alcoholic strength of the wine according to Eq. (7):

$$Q =: K \times° A \times L \times P \qquad (7)$$

where

K is the heat transfer coefficient for each probable alcoholic strength depending on the material of the fermentation tank (1, 3/2, 2).

$°A$ is the probable alcoholic grade of the wine (%vol/vol).

L is the must volume in fermentation (L).

P is the coefficient of thermal development by the metabolic activity of yeasts.

Starting from a wide series of empirical data, and from the equation raised in 1978, Boulton et al. [10] established that with a fermentation ratio of 2 Brix/day the energy released is approximately 0.46 kJ/L h for white wines, while for red wine with a ratio reaching 6 °Brix/day of sugar consumption, the energy released can be set at 1.36 kJ/L h.

According to the Federation Départamentale des Centres d'Etudes et d'Informations Oenologiques of the Gironde-France, FD-CEIOG [12], the heat released in fermentation is defined by Eq. (8):

$$Q \ = \rho \times C_e \times D_t \times VF \times V/100.32 \tag{8}$$

ρ is the density of the must-wine (kg/m^3).

C_e is the specific heat of the must-wine (kJ/kg °C).

D_t is the elevation of the temperature by %vol (K%vol). The mean value of D_t is 2.8 K/%vol.

VF is the fermentation rate (%vol/J).

V is the total volume (m^3).

Flanzy [3] established that the released energy during fermentation can be estimated approximately by knowing the concentration of sugars consumed per hour and liter of must, taking into account that one mole of glucose is equal to 180 g (Eq. (9)):

$$Q : (X/180) \times V \times 100.32 \tag{9}$$

X is the concentration of sugars consumed per liter of must and hour (g/L h). The value of X varies according to the activity of fermentation, with mean values of $X = 2$ g/L h for white wines of slow fermentation at a low temperature and of $X = 7$ g/L h for red wines.
180 g/mole glucose.

V is the total volume of the must to ferment (L).

100.32 kJ/mole glucose.

These mathematical models are difficult to apply in the cellar, so for practical purposes it is more interesting to consider the quantity of sugar consumed per liter of must and per hour. However, there are no reproducible models of the consumption of sugars during fermentation, but the thermodynamic curve of fermentation must be determined for each specific vinification. As an operational parameter for the calculation of cold storage needs of a wine cellar, the maximum value of energy released must be considered (Eq. (10)).

$$Q = \frac{100.32}{180} \times S_o \tag{10}$$

This means that for a must of 12° the heat released is 133 kJ/L of must in fermentation, although for the calculation of cold production equipment it is interesting to refer the total energy produced during fermentation to the duration of the same Q/t.

Part of this energy produced in fermentation is absorbed by the alcohol, the H_2O and the CO_2, which when released into the atmosphere partially or totally cools the system. A total of 180 g of glucose produces 88 g of CO_2 and 92 g of ethanol when they ferment. Each mole of CO_2 formed drags 13.62 kJ for each mole of glucose metabolized. The heat absorbed by the water and the alcohol is determined by the rate of vaporization of the substances, depending on the temperature reached during fermentation and the exterior of the premises [11]. Due to the difficulty of these calculations and the slight thermal decrease, they mean, most authors [2, 3, 10] consider that the heat lost in form of CO_2, ethanol and water equals 10% of the total heat generated.

On the other hand, a certain percentage of the energy released in fermentation is dissipated by the environment, depending on the outside temperature. When the set fermentation temperature is lower than the environment temperature, it produces a thermal transfer from the environment to the tank. The calculation of the energy released or absorbed is based on the conduction/convection heat transfer equations (Eq. (11)) [8–10]:

$$Q = U \times S \times \Delta T \tag{11}$$

U is the heat transfer coefficient. It is a function of the material of constitution of the tank as well as the speed of circulation of the air in the exterior and the presence or not of circulating currents inside the same. According to various authors, the mean value for stainless steel tanks, the static regime of outdoor air and must/indoor wine is $U = 16.72$ kJ/m^2 H °C [3, 8-10] or U = 4.64 w/m^2.°K [3, 18].

S is the outer surface of the tank in contact with the environment.

ΔT is the temperature difference between the must in fermentation with the exterior (°C or °K).

If fermentation tank (or later of storage) is located outside the winery, the solar thermal input is important in regions with high isolation. In order to calculate the energy input, it is necessary to take into account the degree of incidence of the solar rays on the surface of the deposit. Flanzy [3] considers that this thermal contribution varies between 400 w/m^2 in winter and 800 w/m^2 in summer for northern countries. Generally speaking, in Spain, the values can vary between 700 and 1100 w/m^2, respectively. On the other hand, during the night, a significant cooling of the fermentation mas takes place. In complex calculations, involving many variables not always known, this heat dissipation is not taken into account when calculating the cold storage needs, being a margin of safety of the calculations made.

According to what has been said so far, the heat produced during the fermentation process to be dissipated by the application of cold is (Eq. (12)):

$$Q_{total} = Q_{fermentation} - Q_{dissipated\ by\ CO_2,\ H_2O\ and\ ethanol} \pm Q_{ambient} \tag{12}$$

4. Refrigeration requirements for the chemical stabilization of wines

Freshly fermented wine is a saturated solution of tartaric salts whose solubility depends on the alcoholic strength and temperature. In order to avoid the presence of soaps once the wine is bottled, it is necessary to produce in the winery the insolubility and subsequent precipitation of these tartaric salts, mainly potassium bitartrate and calcium tartrate. For this, the wine is subjected to low temperatures modifying its solubility. This must refrigeration presents other side effects of great importance: precipitation of coloring matter and unstable proteins, insolubilization of colloids and reduction of the wine microbial load and facilitates the subsequent process of microbiological stabilization

According to Boulton [13], Maujean [29] and Moutonet et al. [30, 31], the formation of tartrate crystals follows a kinetic of the form (Eq. (13)):

$$[Tartrates]/t = K_v \times N \times (C_a - C_s)^F \tag{13}$$

K_v is the constant that depends on the concentration in salts of the wine and its temperature.

N is the number of existing crystals per ml of wine.

C_a is the concentration of the existing tartrates.

C_s is the concentration of saturation.

F is the conversion factor. It ranges between 5 and 7.

The tartaric stabilization can be carried out discontinuously and continuously. The traditional or continuous stabilization is based on cooling the wine to a temperature close to the freezing temperature set in

$$\mathrm{Ta} = \frac{\text{alcoholic degree } - 1}{2},$$

which means reaching temperatures of $-5/-6°C$. Once the wine has been cooled at this temperature, it is stored in isothermal tanks and they remain until Tsat control data, conductivity or other stability tests result in the stabilization of the wine [2, 18, 32]. This guard time lasts between 7 and 10 days. The modern stabilization systems, continuous or semicontinuous, are based on the refrigeration of the wine to a temperature close to $0°C$ or slightly lower $(-2.5°C)$ with addition of microcrystals of tartrates in variable concentration (generally 4 g/L) and continuous stirring contact method. With these procedures, the treatment time is reduced from 7–10 days to 60–90 min [12, 33]. In both cases after the treatment, the wine already treated gives its cooling energy to the wine that enters by a plate exchanger. Subsequently, it is subjected to a process of filtration by earth or plates to eliminate crystals.

The refrigeration capacity required to cool the wine until the stabilization temperature of $-5/-6°C$ (batch system) to $-2.5/0°C$ (continuous system) is defined by the expression (Eq. (14)) [3, 8–10]:

$$dQ/dt = m \times C_e \times Dt \tag{14}$$

dQ/dt is the cooling capacity per unit of time (kJ/h).

m is the mass flow of wine (kg/h). $m = v \times r$.

v is the volumetric flow rate (m³/h).

r is the density (kg/m³).

C_e is the specific heat of the wine that according to author is C_e = 3.99 kJ/kg °C [16]; C_e = 4.18 kJ/kg °C [3, 20]; C_e = 4.5 kJ/kg°C [10].

Dt is the (initial temperature–final temperature) of the wine.

5. Refrigeration production techniques for cooling musts and crushed-grapes in preformentative operations

For the refrigeration of white wine must, until the temperature of the debourbage or cryomaceration and for the decrease of the temperature of red wine crushed-grapes to the one stablished in fermentation, indirect and direct systems of heat transfer may be used. Among the indirect systems of possible application in the winery, the refrigeration equipment with scraped surface evaporator or with evaporator of concentric tubes and the exchangers are described. As direct methods, CO_2 solids and liquid CO_2, known as carbonic snow, are used.

5.1. Refrigeration of indirect methods

The indirect refrigeration systems most commonly used in the winery are plaque exchangers, tubular exchangers and spiral exchangers. The tubular exchangers consist of a central conduct, of small diameter through which the must or wine circulates, which is concentrically in the interior of a tube of greater diameter through which circulates the refrigerating fluid. The diameter of the inner tube is determined by the viscosity of the fluid flowing through it. Diameters greater than 75–90 mm are recommended for musts and crushed-grapes; for wine, diameters of 50 mm are optimal. The exchange surface and the number of tubes required by the thermal transfer equations will be seen below.

The plaque exchangers consist on fine rectangular surfaces through which the refrigerant and must circulate counterflow. The separation between the plaques does not exceed 10mm and have rough surfaces to create turbulence between the exchange fluids

In the spiral exchangers, the must/crushed-grapes enter at one end and run along a spiral path until it leaves the center axis. At the same time, the refrigerant fluid counterflows on the opposite side.

The cooling power generated by the refrigerant in the heat exchanger is defined by the general energy transfer equation (Eq. (15)) [8, 9, 24]:

$$dQ/dt = \rho \times V \times dT/dt = F_T \times U \times S \times (\Delta T)_{ml} = W \times C_e \times (t_1 - t_2) = W' \times \lambda \qquad (15)$$

where

dQ/dt is the dissipated energy per unit of time (kJ/h).

ρ is the must density (kg/m^3).

V is the tank volume (m^3).

dT/dt is the must temperature variation per unit of time (°C/h).

F_T is the correction factor depending on the must and the refrigeration fluid. It is a measure of the thermal efficiency of the exchange.

U is the global coefficient of heat transfer (w/m^{2}°C). Characteristics of each type of exchanger and the conditions of vinification and outdoor environment.

S is the exchange surface (m^2).

$(\Delta T)_{ml}$ is the logarithmic mean temperature difference between glycol water and must (Eq. (16))

$$(\Delta T)_{ml} = \frac{(t_{em} - t_{sa}) - (t_{sm} - t_{ea})}{\ln \frac{(t_{em} - t_{sa})}{(t_{sinm} - t_{ea})}}$$ (16)

W is the mass flow of refrigerant (kg/h).

C_e is the specific heat of refrigerant fluid (kJ/kg°C).

t_{em} is the initial temperature of must (°C).

t_{sm} is the final temperature of must (°C).

W' is the vaporization rate of the refrigerant (kg/h).

λ is the latent heat of vaporization of the refrigerant (kJ/kg).

Geankoplis [9] and McCabe et al. [8] propose a formula (Eq. (17)) for the calculation of the thermal transfer coefficient U, the Donohue expression applied for low values of the Reynolds number, *Re*:

$$\frac{UD_o}{k} = 0.2 \left(\frac{D_o \sqrt{G_a} G_m}{\mu} \right)^{0.6} \left(\frac{C_e \mu}{k} \right)^{0.33} \left(\frac{\mu}{\mu w} \right)^{0.14}$$ (17)

U is the thermal exchange coefficient (w/m$^{2\circ}$C).

k is the thermal conductivity of the must (w/m$^{2\circ}$C).

D_o is the outer diameter of the tubes (m).

G_a is the mass transfer rate of the glycol water (kg/m^{2}h) equal to m_a/s_b.

G_m is the mass transfer speed of must/crushed-grapes (kg/m^{2}h) equal to m_m/S_c.

m_a, m_m is the mass per unit of time of glycol water and must in circulation (kg/h).

S_a, S_c is the internal and external contact surfaces as a function of the number of tubes (m^2).

μ: is the must/crushed-grapes viscosity (cP).

C_e is the specific heat of must/crushed-grapes (kJ/kg°C).

μ_w is the specific heat of glycol water (kJ/kg°C).

This complex expression is difficult to apply in practice by relying on factors not always known in oenology, so in a generally accepted form empirically obtained values of U are used.

For tubular exchangers used in musts, the value of U is set at 400–1300 w/m$^{2\circ}$C for smooth tubes and at 1700–2400 with rough surface [16], from 500 to 900 w/m$^{2\circ}$C [8], from 600 to 900 w/m$^{2\circ}$C [13], from 750 to 1200 w/m$^{2\circ}$C [34], from 700 to 1100 w/m$^{2\circ}$C [3, 35].

In plate exchangers $U = 2900–4800$ w/m^2°C [10], at 3500–6500 w/m^2°C [8], from 2400 to 2600 w/m^2°C [10, 13], of 2000 w/m^2°C [3].

In spiral exchangers $U = 1700$ w/m^2°C [10], of 2000–2100 w/m^2°C [8], from 760 to 1060 w/m^2°C [10, 13, 36].

5.2. Direct refrigeration systems

In direct refrigeration system, two fluids that exchange energy are physically in contact. In oenology, the inert gases N_2 and CO_2 are used as refrigerating fluids, since when vaporizing at low temperatures they absorb heat from the must/crushed-grapes.

Of the two inert gases mentioned above, CO_2 in solid and liquid forms is the most used in oenology, due to its low sublimation temperature at atmospheric pressure –72.4°C, added contribution of inert atmosphere of conservation, possibility of partial freezing of the must with the consequent sugar concentration, ease of handling and no residues.

The cooling capacity provided by CO_2 in solid form is defined by the following expression (Eq. (18)) [4, 8–10, 13]:

$$dQ = \rho \times V \times C_e \times (T_1–T_2) = M \times (\lambda_{FS} + \lambda_{VP}) \tag{18}$$

If ice is produced due to the freezing of the water from the must to this expression (Eq. (19)), we must add the energy due to the sublimation heat of CO_2:

$$Q_{H_2O} = m \times \lambda_{H_2O}, \; resultado : dQ = m \times \lambda_{H_2O} + \rho \times V \times C_e \times (T_1–T_2) = M \times (\lambda_{FS} + \lambda_{VP}) \tag{19}$$

where

m is the formed ice mass (kg).

λ_{H_2O} is the latent heat of water fusion (0.108 kJ/kg).

ρ: is the must/crushed-grapes density (°C).

V is the must/crushed-grapes volume (m^3).

C_e is the specific heat of must/crushed-grapes (kJ/kg °C).

T_1 is the initial temperature of must/crushed-grapes (°C).

T_2 is the final temperature of must/crushed-grapes (°C).

M is the mass of CO_2 in solid form required for refrigeration (kg).

λ_{FS} is the latent heat of fusion of solid CO_2 (573 kJ/kg).

λ_{VP} is the latent heat of vaporization of liquid CO_2 (393 kJ/kg).

To form 1 kg of ice in the must mass, it is necessary to add 0.58 kg of CO_2 to the freezing temperature of the must (–2.5 to 3.0°C). In the refrigeration of musts, wines and crushed-

grapes, the formation of ice is unadvisable to increase the risk of subsequent physical and chemical instability, so that for the purpose of calculating the cooling power, generally the energetic term Q_{SB} is not taken into account.

According to Boulton et al. [10, 13], in order to reduce the temperature of a white wine must (5°C), it is necessary to use 4.42 kg of solid CO_2 for each hectoliter of must. Geankoplis [9] stablishes that due to the energy losses by the deposit walls, this quantity must increase to 4.6 kg/hl.

The use of CO_2 in liquid form supposes a decrease of the dissipated energy of the deposit in relation to the solid ice, since in the energy transfer equation the latent heat of fusion of CO_2 does not come into play, resulting (Eq. (20)):

$$dQ = m \times \lambda_{H_2O} + \rho \times V \times C_e \times (T_1 - T_2) = M \times \lambda_{VP} \tag{20}$$

As stated above, it is not advisable to form ice from the water of constitution of the must or crushed-grapes, whereby the above expression is modified as follows (Eq. (21)):

$$dQ = \rho \times V \times C_e \times (T_1 - T_2) = M \times \lambda_{VP} \tag{21}$$

ρ: is the must/crushed-grapes density (kg/m^3).

V is the must/crushed-grapes volume (m^3).

C_e is the must/crushed-grapes specific heat (kJ/kg °C).

T_1 is the initial temperature of must/crushedgrapes (°C).

T_2 is the final temperature of must/crushed-grapes (°C).

M is the mass of CO_2 in solid form required for refrigeration (kg).

λ_{VP} is the latent heat of vaporization of liquid CO_2 (393 kJ/kg).

6. Cold production techniques for the control of fermentation temperature

In order to dissipate the energy produced during fermentation in the oenological industry, water spray or shower systems, refrigeration liners and internal plaques or snakes are used. The external exchangers are also used, the description of which has been made in the previous section as it is the most used mechanism in the refrigeration of musts and crushed-grapes in preformentative operations.

6.1. Water shower

It consists on spraying the walls of the fermentation tank with water from an upper ring connected to a general feed system. A very fine and homogeneous layer of laminar water is generated, which descends through the walls and is normally collected in channels arranged in the lower part of the tank. An automatic control allows the opening and closing of solenoid

valves according to the temperature inside the tank and the preset. The refrigeration mechanism by conduction and convection is based on the removal of energy from the tank by partial vaporization of the circulation system water.

Thermodynamically, it is the most unfavorable refrigeration system and the one that uses the greater volume of water, which supposes a greater environmental cost. These cases are recommended where no refrigerated water is available (below 20°C). For this reason, it is used with efficiency in the control of fermentation in red wine vinifications, not being able to be applied in any case for rose and white wine vinifications.

The refrigeration power of the water curtain is defined by the heat of vaporization of the water at room temperature. The heat of its vaporization is the sum of its sensible heat in liquid state and the latent heat of vaporization corresponding to the change in water-vapor station. For calculation purposes, the refrigeration power of the water due to sensible heat is defined by (Eq. (22)):

$$Q_S = U \times S \times (T_{\text{inside tank}} - T_{\text{curtain water}}) \tag{22}$$

where

K is the thermal transfer coefficient. For stainless steel tanks and water circulation in a thin layer laminar regime on the surface, the value of U is of the order of 100 w/m$^{2\circ}$C [3, 7, 8, 35].

S is the surface of the tank in contact with the water curtain.

The refrigeration power due to the latent heat of water vaporization is (Eq. (23)):

$$Q_1 = H \times S \times (T_{air} - T_{wet\ air\ bulb}) \tag{23}$$

where

H is the coefficient of thermal transmission by convection between the water curtain and the tank surface. According to McCabe et al. [8] and Geankoplis [9], Lamúa [37] takes values between 10 w/m$^{2\circ}$C for closed rooms without air circulation and 40 w/m$^{2\circ}$C for exterior conditions subjected to wind action.

S is the surface of the tank in contact with the water curtain.

The wet bulb temperature of the air can be determined on a psychometric diagram and depends on the room temperature and the relative humidity of the air.

Only if the water temperature exceeds the humid bulb temperature of the air, vaporization has place and therefore a dissipation of energy of the tank, since if it is lower a condensation of the air humidity occurs on the tank.

6.2. Refrigerating shirts

The use of refrigeration shirts is currently the most widespread fermentation control system in both white and red winemaking. Traditionally, they have been constructed in stainless steel

and are fixedly arranged in the upper part of the tank, occupying between 15 and 30% of the surface. In the recent years, some manufacturers are using new polymers of medium rigidity and high resistance that makes possible their installation on the tank according to the needs of the campaign. As to their disposition, and in agreement with the results of several investigations that advise for vinifications in red wine the use of fermentation tanks of equal height and base diameter, the shirts are installed covering the greatest part of the side surface of the deposit, reaching in some cases 90% of it. This new system allows a homogeneous control of fermentation, avoiding the problem of the thermal stratification that takes place with large diameters.

Similar to the tubular and plaque exchangers, the exchanged energy is defined by the general energy transfer equation (Eq. (24)) [8, 10, 13, 38]:

$$dQ/dt = \rho \times V \times dT/dt = F_T \times U \times S \times (\Delta T)_{ml} = W \times C_e \times (t_1 - t_2) = W' \times \lambda \quad (24)$$

dQ/dt is the dissipated energy per unit of time (kJ/h).

ρ: is the must density (kg/m^3).

V is the tank volume (m^3).

dT/dt is the must temperature variation per unit of time (°C/h).

F_T is the correction factor depending on the ratio of the must and coolant velocities. It is a measure of the thermal efficiency of the exchange.

U is the global coefficient of heat transfer (w/m$^{2\circ}$C). The coefficient depends on the type of refrigeration jacket, vinification and exterior environment conditions. Based on empirical data, mean values of 12–60 x/m$^{2\circ}$C are stablished [10, 13]. Other authors raise the value of U to 200–600 w/m$^{2\circ}$C [3] or 600–1000 [39].

S is the shirt surface (m^2).

$(\Delta T)_{ml}$ is the logarithmic mean temperature difference between glycol water and must (Eq. (25))

$$(\Delta T)_{ml} = \frac{(t_{em} - t_{sa}) - (t_{sm} - t_{ea})}{\ln \frac{(t_{em} - t_{sa})}{(t_{sm} - t_{ea})}} \quad (25)$$

W is the mass flow of refrigerant (kg/h).

C_e is the specific heat of refrigerant (kJ/kg °C).

t_{em} is the must initial temperature (°C).

t_{sm} is the must final temperature (°C).

W' is the vaporization rate of refrigerant (kg/h).

λ is the vaporization latent heat of refrigerant (kJ/kg).

Two of the cases that take place, the refrigerating fluid changes of state for example R-717 evaporated to 5–7°C (in that case the fluid temperature is constant) or there is no change of state (glycol water), producing a heating throughout the cooling process. As approximate data, it is considered that water enters between 5 and 7°C and exits between 10 and 12°C.

For the purpose of calculating the equipment of the cold production facility, a simplified equation of the above is used (Eq. (26)):

$$Q_c = U \times S \times (T_{\text{inside tank}} - T_{\text{circulating water}})_{\text{ml}} \tag{26}$$

Since the must/wine inside the tank is in steady state and this heat exchange equation is applied for counter current flowing fluids, the term $(\Delta T)_{\text{ml}}$ is simplified to $(T_{\text{inside tank}} - T_{\text{circulating water}})$.

It should be noted that 50% of the refrigerating protein produced by the shirt dissipates in the environment surrounding the tank if it is not well heat-insulated. In case no insulation is available, the required shirt surface must be doubled, or, if appropriate, the cooling capacity is reduced by half for calculation purposes.

The cooling jackets have very low heat transfer coefficients due to the steady state in which the must/wine is located inside the tank. The effectiveness of the refrigeration decreases proportionally with the diameter of the tank, being considered that for normal temperatures of circulation water limiting diameters of more than 4 m, due to the vertical thermal stratification that occurs [10, 13, 35]. If only large diameter tanks are available, the effectiveness decreases in a high percentage, so to maintain it in appropriate values, very low temperatures are required in the glycolic water, close to 1–2°C. According to Bouton et al. [10, 13], if the diameter doubles the surface of the jacket, it is multiplied by four and the volume of the must/wine is refrigerated by eight, maintaining the ratio surface/volume. As an approximate value and only for approximate calculations, 2 m² of cooling jacket per 100 hl of must in fermentation is recommended.

The cooling jackets are used in the tartaric stabilization process of the wines by the system of planting nuclei of crystallization, circulating glycolic water at −7°C to reach temperatures of −1°C.

6.3. Cooling plaques or submerged coils

The coolant fluid flows through an exchanger (plaque or coil) submerged in the must/wine. The refrigeration is based on convection and conduction phenomena.

It is a very economical solution as it does not require special tanks and large accessory installations. It is applied in wine cellars of small and medium capacity that have tanks with volumes never exceeding 300 hl. As an advantage, the possibility of placing them in the zones of maximum thermal generation is at any level and from the beginning of fermentation.

Both plates and coils are constructed of stainless steel and are usually mobile structures that are moved from one tank to another by flexible conducts. Glycol water circulates in its interior at temperatures of 5–7°C or refrigerating fluids with similar evaporating temperature.

The refrigeration capacity generated is calculated in the same way as in the case of outer cooling jackets, taking into account that in this case the exchange surface is double as both sides are in contact with the must/wine (Eq. (27)):

$$Q_c = U \times S \times (T_{\text{inside tank}} - T_{\text{circulating water}})_{\text{ml}} \tag{27}$$

taking U as the same values of those mentioned above.

7. Cold production techniques for the tartaric stabilization of wines

To carry out the tartaric stabilization, the wine is cooled to the temperature previously set according to the system used continuous or discontinuous. The temperature of the wine must be lowered to $-5°$C in discontinuous systems and from 0 to $-2°$C in continuous systems, to cause the crystallization and precipitation of potassium bitartrate and calcium tartrate. The required cold is generally supplied by a scraped surface exchanger, with glycol water or with direct expansion of the refrigerant.

An exchanger with scraped surface is constituted by a cylinder of 0.75–1 m of length and 0.15–0.20 m of diameter, in whose interior a series of pallets is located around an axial axis with a rotation movement between 300 and 600 rpm. Inside the cylinder circulates the wine to be treated. In this way, concentric to the previous one, is arranged a cylinder or cooling jacket through which the refrigerating fluid is counter flow with the wine. The mission of the pallets is to remove and circulate the ice formed and deposited on the wall of the exchanger, around 10–20% according to the treatment temperature. According to McCabe et al. [8] and Geankoplis [9], the energy transferred from the glycolic water or the refrigerating fluid to the wine in a range t is calculated according to the expression (Eq. (28)):

$$\frac{Q}{S} = 2\,Uk\,(Tv - T\alpha)\,\sqrt{\frac{t}{\pi\alpha}} \tag{28}$$

where

Q is the dissipated energy (kJ).

S is the exchange surface (m^2).

U is the global coefficient of heat transfer (w/m$^{2\circ}$C).

K is the wine thermal conductivity (w/m$^{2\circ}$C).

T_v is the wine initial temperature (°C).

T_α: is the initial temperature of glycol water or refrigeration liquid (°C).

t is the total contact time (h).

α: is the thermal diffusivity of wine (w/m$^{2\circ}$C).

$$\frac{UD_\alpha}{k} = 4.9 \left(\frac{D_\alpha V \rho}{\mu}\right)^{0.57} \left(\frac{C_e \mu}{K}\right)^{0.47} \left(\frac{D_a n}{V}\right)^{0.17} \left(\frac{D_a}{L}\right)^{0.37}$$

U is the global coefficient of heat transfer (w/m$^{2\circ}$C).

K is the wine thermal conductivity (w/m$^{2\circ}$C).

D_a is the internal diameter of the exchanger (m).

V is the speed of wine circulating (m/h).

ρ: is the wine density (kg/m^3).

C_e is the wine specific heat (kJ/kg$^\circ$C).

m is the wine viscosity (cP).

n is the stirring speed of the blades (rph).

L is the length of the exchanger (m).

Due to the difficulty of calculation, for practical purposes, the dimensioning of a scraped surface exchanger is performed according to the simplified energy transfer equation (Eq. (29)) [10, 13, 34].

$$Q_c = U \times S \times (T_{\text{wine}} - T_{\text{glycolic water}})_{\text{ml}} \tag{29}$$

Q is the dissipated energy (kJ).

U is the global coefficient of heat transfer (w/m$^{2\circ}$C).

S is the exchange surface (m^2).

$(\Delta T)_{\text{ml}}$ is the logarithmic mean temperature difference between glycol water/refrigerant and wine (Eq. (30)).

$$(\Delta T)_{\text{ml}} = \frac{(t_{em} - t_{sa}) - (t_{sm} - t_{ea})}{ln \frac{(t_{em} - t_{sa})}{(t_{sm} - t_{ea})}} \tag{30}$$

As values of U, are taken those empirically calculated by different authors. According to López [39], U = 580–870 w/m$^{2\circ}$C. For McCabe et al. [40], U = 700–900 w/m$^{2\circ}$C. Boulton et al. [10, 13] establish an average value of U = 600–2000 w/m$^{2\circ}$C.

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