CHAPTER 26

BEVERAGES

THIS chapter discusses the processes and use of refrigeration in breweries, wineries, and carbonated beverage plants.

BREWERIES

MALTING

Malt is the primary raw ingredient in brewing beer. Although adjuncts such as corn grits and rice contribute considerably to the composition of the extract, they do not possess the necessary enzymatic components required for preparing the wort. They lack nutrients (amino acids) required for yeast growth, and contribute little to the flavor of beer. Malting is the initial stage in preparing raw grain to make it suitable for mashing. Traditionally, this operation was carried out in the brewery, but in the past century, this phase has become so highly specialized that it is now almost entirely the function of a separate industry.

Various grains such as wheat, oats, rye, and barley can be malted; however, barley is the predominate grain used in preparing malt because it has a favorable protein-to-starch ratio. It has the proper enzyme systems required for conversion, and the barley hull provides an important filter bed during lautering. Also, barley is readily available in most of the world.

There are three steps to malting barley. In **steeping**, the raw grain is soaked in 40 to 65°F water for 2 to 3 days. The moisture content of the barley kernel increases from 12% to approximately 45%. The water is changed frequently and the grain is aerated. After two or three days, the kernels start to germinate and the white tips of rootlets appear at the end of the kernels. At this time, the water is drained and the barley is transferred to where it is germinated.

During 4 to 5 days of **germination**, the kernel continues to grow. The green malt is constantly turned over to ensure uniform growth of the kernels. Slowly revolving drums can be used to turn over the growing malt. In a compartment system, slowly moving, mechanically driven plowlike agitators are used for mixing. Cool (50 to 65°F) saturated moist air is used to maintain temperature and green malt moisture levels. At the desired stage in its growth, the green malt is transferred to a kiln.

Kilning, the final step, stops the growth of the barley kernel by reducing its moisture level. Warm (120 to 150°F) dry air is used to remove moisture from the green malt. Kilning is usually done in two stages. First, the malt's moisture content is reduced to approximately 8 to 14%; then, the heat is increased until the moisture is further reduced to about 4%. Using this heating procedure reduces excessive destruction of enzymes. The desired color and aroma are obtained by controlling the final degree of heat.

After kilning, the malt is cleaned to separate dried rootlets from the grain, which is then stored for future use. The finished malt differs from the original grain in several significant ways. The hard endosperm was modified and is now chalky and friable. The enzymatic activity has been greatly increased, especially alpha amylase, which is not present in unmalted barley. The moisture content is reduced, making it more suitable for storing and subsequent crushing. It now has a distinctive flavor and aroma, and the starches and enzymes are readily extractable in the brewhouse.

PROCESS ASPECTS

Two distinct types of chemical reactions are used in brewing beer. **Mashing** is carried out in the brewhouse. Starches in the malted grain are hydrolyzed into sugars and complex proteins are broken down into simpler proteins, polypeptides, and amino acids. These reactions are brought about by crushing the malt and suspending it in warm (100 to 122°F) water by means of agitation in the mash tun. When adjuncts (usually corn grits or rice) are used, a portion of the malt is cooked separately with the adjunct. After boiling, this mixture is combined with the main mash, which has been proportioned so that a combining temperature generally in the range of 145 to 162°F results. Within this temperature range, the alpha and beta amylases degrade the starch to mono-, di-, tri-, and higher saccharides. By suitably choosing a time and temperature regimen, the brewer controls the amount of fermentable sugars produced. The enzyme diastase (essentially a mixture of alpha and beta amylase), which induces this chemical reaction, is not consumed but acts merely as a catalyst. Some of the maltose is subsequently changed by another enzyme, maltase, into a fermentable monosaccharide, glucose.

Mashing is complete when the starches are converted to iodine-negative sugars and dextrins. At this point, the temperature of the mash is raised to a range of 167 to 172°F, which is the "mashing-off" temperature. This stops the amylolytic action and fixes the ratio of fermentable to nonfermentable sugars. The **wort** is separated from the mash solids using a lauter tub, a mash filter, or other proprietary equipment (MBAA 1999). Hot water (168 to 170°F) is then "sparged" through the grain bed to recover additional extract. Wort and sparge water are added to the brew kettle and boiled with hops, which may be in the form of pellets, extract, or whole cones. After boiling, the brew is quickly cooled and transferred to the fermentation cellar, where yeast is added to induce fermentation. Figure 1 shows a double-gravity system with grains stored at the

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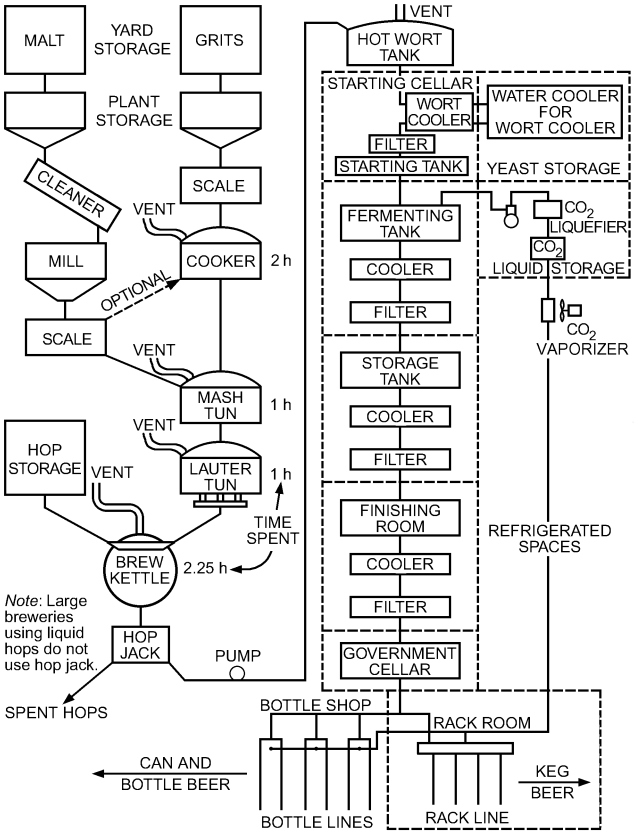


Fig. 1 Brewery Flow Diagram

top of the brewhouse. As processing continues, gravity creates a downward flow. Hot wort from the bottom of the brewhouse is then pumped to the top of the stockhouse, where it is cooled and again proceeds by gravity through fermentation and lagering.

After the wort cools, yeast and sterile air are injected into it. The yeast is pumped in as a slurry at a rate of 1 to 3 lb of slurry per barrel of wort. Normally, oil-free compressed air is filtered and treated with ultraviolet light and then added to the wort, which is nearly saturated with approximately 8 ppm of oxygen. However, the wort may also be oxygenated with pure oxygen.

Fermentation takes place in two phases. During the first phase, called the respiratory or aerobic phase, the yeast consumes the oxygen present. It uses a metabolic pathway, preparing it for the anaerobic fermentation to follow. The process typically lasts 6 to 8 h.

Oxygen depletion causes the yeast to start anaerobically metabolizing the sugars in the extract, releasing heat and producing CO_2 and ethanol as metabolic by-products.

During early fermentation, the yeast multiplies rapidly then more slowly as it consumes the available sugars. Normal multiplication for the yeast is approximately 3 times. A representative value for the heat released during fermentation is 280 Btu/lb of extract (sugar) fermented.

Wort is measured by the saccharometer (measures sugar content), which is a hydrometer calibrated to read the percentage of maltose solids in solution with water. The standard instrument is the Plato saccharometer, and the reading is referred to as percentage of solids by saccharometer, or degrees Plato (°P). Table 1 illustrates the various data deducible from reading the saccharometer.

The same instrument is used to check fermentation progress. Although it still gives an accurate measure of density of the fermenting liquid, it is no longer a direct indicator of dissolved solids because the solution now contains alcohol, which is less dense than water. This saccharometer reading is called the apparent extract, which is always less than the real extract (apparent attenuation is calculated from the hydrometer reading of apparent extract and the original extract). In engineering computations, 81% of the change in apparent extract is considered a close approximation of the change in real extract. Thus, 81% of the difference between the solids shown in Table 1 for saccharometer readings before and after fermentation represents the mass of maltose fermented. This weight in pounds per barrel times 280 Btu/lb gives the heat of fermentation in Btu per barrel. (Each barrel has a capacity of 31 gal.) The difference between the original solids and mass of fermented solids gives the residual solids per barrel. It is assumed that there is no change in the volume because of fermentation. The specific heat of beer is assumed to be the same as that of the original wort, but the mass per barrel decreases according to the apparent attenuation.

Table 1 Total Solids in Wort

% Solids*	Specific Gravity	Weight per Barrel, lb		Specific Heat, Btu/lb·°F
		Total	Solids	
0	1.0000	258.7	0.00	1.000
1	1.0039	259.7	2.60	0.993
2	1.0078	260.7	5.21	0.986
3	1.0118	261.8	7.85	0.979
4	1.0157	262.8	10.51	0.972
5	1.0197	263.8	13.19	0.965
6	1.0238	264.9	15.89	0.958
7	1.0278	265.9	18.61	0.951
8	1.0319	267.0	21.36	0.944
9	1.0360	268.0	24.12	0.937
10	1.0402	269.1	26.91	0.930
11	1.0443	270.2	29.72	0.923
12	1.0485	271.2	32.55	0.916
13	1.0528	272.4	35.41	0.909
14	1.0570	273.4	38.28	0.902
15	1.0613	274.6	41.18	0.895
16	1.0657	275.7	44.11	0.888
17	1.0700	276.7	47.06	0.881
18	1.0744	277.9	50.03	0.874
19	1.0788	279.1	53.03	0.867
20	1.0833	280.2	56.05	0.860

*Saccharometer readings.

Bottom-fermentation yeast (e.g., *Saccharomyces uvarium*, formerly *carlsbergensis*) is used in fermenting lager beer. Top-fermentation yeast (e.g., *Saccharomyces cerevisiae*) is used in making ale. They are so called because, after fermentation, one settles to the bottom and the other rises to the top. A more significant difference between the two types is that in the top-fermentation type, the fermenting liquid is allowed to attain a higher temperature before a continued rise is checked. The following characteristics of brewing ale make it different from brewing lager:

- A more highly kilned darker malt is used.
- Malt forms a greater proportion of the total grist (less adjunct).
- Infusion mashing is used and a wort of higher original specific gravity is generally produced.
- More hops are added during the kettle boil.
- A different yeast and temperature of fermentation are used.

Therefore, ale may have a somewhat higher alcohol content and a fuller, more bitter flavor than lager beer. With bottom-fermentation yeasts, fermentation is generally carried out between 45 and 65°F and most commonly between 50 and 60°F. Ale fermentations are generally carried out at somewhat higher temperatures, often peaking in the range of 70 to 75°F. In either type, the temperature during fermentation would continue to rise above that desired if not checked by cooling coils or attemperators, through which a cooling medium such as propylene glycol, ice water, brine, or ammonia is circulated. In the past, these attemperators were manually controlled, but more recent installations are automatic.

PROCESSING

Wort Cooling

To prepare boiling wort from the kettle for fermentation, it must first be cooled to a temperature of 45 to 55°F. To avoid contamination with foreign organisms that would adversely affect subsequent fermentation, cooling must be done as quickly as possible, especially through the temperatures around 100°F. Besides the primary function of wort cooling, other beneficial effects accrue that are essential to good fermentation, including precipitation, coagulation of proteins, and aeration (natural or induced, depending on the type of cooler used).

In the past, the Baudelot cooler was almost universally used because it is easy to clean and provides the necessary wort aeration. However, the traditional open Baudelot cooler was replaced by one consisting of a series of swinging leaves encased within a removable enclosure into which sterilized air was introduced for aeration. This modified form, in turn, has virtually been replaced by the totally enclosed heat exchanger. Air for aeration is admitted under pressure into the wort steam, usually at the discharge end of the cooler. The air is first filtered and then irradiated to kill bacteria, or it can be sterilized by heating in a double-pipe heat exchanger with steam. By injecting 0.167 ft^3 of air per barrel (bbl) of wort, which is the amount necessary to saturate the wort, normal fermentation should result. The quantity can be accurately increased or diminished as the subsequent fermentation indicates.

The coolant section of wort coolers is usually divided into two or three sections. For the first section, a potable source of water is used. The heated effluent goes to hot-water tanks where, after additional heating, it is used for subsequent mashing and sparging in the brew house. Final cooling is done in the last section, either by direct expansion of the refrigerant or by means of an intermediate coolant such as chilled water or propylene glycol. Between these two, a third section may be used from which warm water can be recovered and stored in a wash-water tank for later use in various washing and cleaning operations around the plant.

Closed coolers save on space and money for expensive cooler room air-conditioning equipment. They also allow a faster cooling rate and provide accurate control of the degree of aeration. To maintain good heat transfer, closed coolers may be flushed with hot water between brews or circulated for a few minutes with cleaning solutions. More thorough cleaning, perhaps done weekly, is accomplished by much longer periods of circulation with cleaning solutions, such as 2 to 4% caustic at 175°F. Reverse flow of the cleaning solution may also be used to help dislodge deposits of protein, hops, and other materials.

In selecting a wort cooler, consider the following:

- The cooling rate should allow the contents of the kettle to be cooled in 1 or, at most, 2 h.
- The heat transfer surfaces to be apportioned between the first section, using an available water supply, and the second section, using refrigeration, should make the most economical use of each of these resources. Cost of water, its temperature, and its availability should be balanced against the cost of refrigeration. Usual design practice is to cool the wort in the first section to within 10°F of the available water.
- Usable heat should be recovered (effluent from the first section is a good source of preheated water). After additional heating, it can be used for succeeding brews and as wash water in other parts of the plant. At all times, the amount of heat recovered should be consistent with the overall plant heat balance.
- Meticulous sanitation and maintenance costs are important.

Wort cooler size is determined by the rate of cooling desired, rate of water flow, and temperature differences used. A brew, which may vary in size from 50 to 1000 bbl and over, is ordinarily cooled in 1 or, at most, 2 h. Open coolers are made in stands up to about 20 ft long. Where more length is needed, two or more stands are operated in parallel.

Open coolers are best operated with a wort flow of 10 to 11.5 bbl/h per foot of stand. As flow increases beyond this rate, an increasingly larger part of the wort splashes from the top tube of the cooler and drops directly into the collecting pan below without contacting the cooler surfaces. An increased amount of wort flowing over the surfaces must be subcooled to offset what has been bypassed.

In plate coolers, this bypassing does not occur, and wort velocities can be increased to a point where friction pressure through the cooler approaches the maximum design pressure of the press and gasketing. The number of passes and streams per pass afford the designer much latitude in selecting the most favorable parameters for optimum performance and economical design. This design is based on (1) the specific heat of wort, (2) its initial temperature and range through which it is to be cooled, (3) temperature of the available water supply, and (4) ratio of the quantity of cooling water to wort that is to be used. Design and operating features of a typical plate cooler are as follows:

Specifications

Quantity of wort to be cooled	17,000 lb/h
Temperature of hot wort	210°F
Temperature of cooled wort	40°F
Temperature of available water (maximum)	70°F
Water used, not to exceed	34,000 lb/h
Temperature of water leaving cooler	140°F
Temperature of wort leaving first section of cooler	80°F
Temperature of incoming recirculated chilled water	34°F

Plate cooler (first section)

Number of plates	40
Heat transfer surface per plate	4.3 ft^2
Heat transfer surface in first section	172 ft^2
Number of passes	5
Number of streams per pass	4
Water flow rate	34,000 lb/h
Wort flow rate	17,000 lb/h

Plate cooler (second section)

Number of plates	24
Heat transfer surface per plate	4.3 ft^2
Heat transfer surface in second section	103 ft^2
Number of passes	3
Number of streams per pass	4
Chilled-water flow rate	52,000 lb/h

A shell-and-tube or plate cooler with two stages of cooling can cool the wort efficiently. In the first (hot) stage, potable water is used counterflow to the wort, and the usual discharge temperature is about 169 to 171°F. This hot water is then used in the following brews at various blended temperatures. Excess is used in the brewery's general operations.

The second stage of wort cooling is accomplished at about 36°F by a closed system of refrigerated water through a closed cooler, which cools the wort to 50°F or lower, depending on the brewer. Lower-temperature water (33°F) may be used in open units where no danger of freezing exists.

Wort cooling may be accomplished in one stage, depending on the potable water temperature available and plant refrigeration capacity. If chilled water (33 to 36°F) is available, water use is typically 1.1 to 1.4 times the volume of wort and exits the cooler at temperatures suitable for immediate use in brewing. If ambient water is used, much larger volumes are required and water costs must be considered. Also, excess hot water may be sewered, leading to increased waste effluent charges.

Fermenting Cellar

After cooling, the wort is pitched with yeast and collected in a fermenting tank, where respiration and fermentation occur according to the chemical reaction previously discussed. The daily rate of fermentation varies depending on the operating procedure adopted in each plant. On the first day, a representative rate might be 2 lb of converted maltose per barrel of wort. The rise in temperature caused by fermentation and by the growth and changing physiology of the yeast increases this rate to 7 lb/bbl on the second day. By now, the maximum desired temperature has been attained, and a further rise is checked by an attemperator, so that on the third day another 7 lb is converted. This rate continues through the fourth day. Two examples of the fermentation rate follow; one is for normal-gravity brewing, and the other is for high- (heavy) gravity brewing.

Example 1 Normal-Gravity Brewing

Fermentation Day	°Plato	Real Extract	Extract per bbl, lb	Extract Fermented per bbl, lb
0	11	11.0	29.63	—
1	10	10.2	27.38	2.25
2	8	8.6	22.95	4.43
3	5	6.1	16.12	6.83
4	3	4.5	11.81	4.31
5	2.5	4.1	10.75	1.06
				18.88

Example 2 High-Gravity Brewing

Fermentation Day	°Plato	Real Extract	Extract per bbl, lb	Extract Fermented per bbl, lb
0	16	16.0	43.97	—
1	15	15.2	41.64	2.33
2	12	12.8	34.73	6.91
3	7	8.7	23.11	11.51
4	4	6.3	16.66	6.56
5	3.5	5.9	15.58	1.08
				28.39

By now, the amount of unconverted maltose remaining in the beer is greatly diminished. Because alcohol, carbon dioxide, and other products of fermentation inhibit further yeast propagation, the action nearly stops on the fifth day, when only about 3 lb is converted per barrel. At this stage the yeast begins to flocculate (clump together) and either settles to the bottom of the fermenter (bottom yeast) or rises to the top (top yeast). Because of the reduced fermentation rate, the temperature of the beer begins to fall, either as the result of increased attemperation applied to the tank itself, heat loss from the tank to the surrounding area, or both. Many fermentation programs call for the beer to be cooled to 35 to 45°F at this time. This period of more rapid cooling helps settle the yeast. At the completion of this cooling period, the fermentation rate is essentially zero, and the beer is ready to be transferred off the settled yeast. Complete fermentation generally occurs in about 7 days. The introduction of new types of beers (e.g., reduced calorie, reduced alcohol) and the more general use of high-gravity brewing have led to the use of a variety of fermentation programs both between brewers making the same product and within the same brewery for different products.

Complete fermentation can be accomplished in less than 7 days, but most modern brewers take 7 to 10 days for the fermentation and subsequent cooling. The time depends on original gravity, whether a secondary fermentation is used, and available cooling capacity. Most brewers cool beer to between 42 and 38°F after ending fermentation or after the final days of quick cooldown in the fermenting tank. In addition, the long rest allows time for the yeast to settle. Some brewers agitate the beer in cylindrical fermenters, which enables them to ferment the beer faster and then to separate out the yeast by centrifuge. Most brewers cool the beer to the desired 29 to 45°F temperature before it goes into storage for resting and settling between fermentation and final aging.

Fermenting Cellar Refrigeration

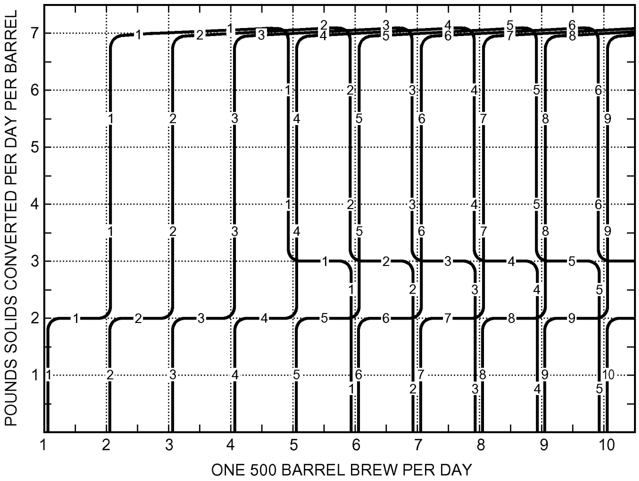
The agitation necessary for heat exchange between the attemperator and the beer is provided partly by convection resulting from temperature gradients in the beer. Agitation is principally by the ebullition caused by the carbon dioxide (CO_2) bubbles rising to the surface of the liquid. In estimating the heat transfer surface required, a heat transfer rate range from 15 to 30 $Btu/h \cdot ft^2 \cdot °F$ is reasonable. Heat loss from tank walls and the surface of the liquid may be disregarded when calculating attemperator coil surface requirements. However, if the room temperature drops appreciably below 50°F, heat dissipated through the metal tank walls becomes important. Depending on the degree of heat dissipation, fermentation may be retarded or even inhibited. In such instances, insulating the fermenter walls and bottom is required so that control over heat removal remains in the attemperator.

Refrigeration requirements are based on the maximum volume of wort being fermented, as illustrated by Example 3.

Example 3. Figure 2 illustrates the volume of wort production based on a 500 bbl/day production rate. Days are represented by the abscissa, and the pounds of solids converted per day by the ordinate. The individual brews in fermentation on any particular day are additive. For example, on the fifth day, Brew No. 1 is finishing with a conversion rate of 3 lb/bbl for that day; Brew No. 5, which is just beginning the fermentation cycle, is fermenting at the rate of 2 lb/bbl; and Brews No. 2, 3, and 4 are each at the maximum rate of 7 lb/bbl per day. The total solids fermented on this day are 26 lb/bbl for the 2500 bbl in fermentation, totaling 13,000 lb of solids converted per day. Because the heat of fermentation is 280 Btu/lb, the refrigeration load is

$$(13{,}000 \times 280)/(24 \times 12{,}000) = 12.6 \text{ tons}$$

Calculations for sizing attemperators must consider the (1) internal dimensions of the fermenting tank and its capacity; (2) temperature



Brew 5	2 lb × 500 bbl =	1000 lb
Brew 4	7 lb × 500 bbl =	3500 lb
Brew 3	7 lb × 500 bbl =	3500 lb
Brew 2	7 lb × 500 bbl =	3500 lb
Brew 1	3 lb × 500 bbl =	1500 lb
	26 lb	13,000 lb

Fig. 2 Solids Conversion Rate

difference between the coolant and fermenting beer; (3) maximum daily sugar conversion rate; and (4) heat evolved, which is at the rate of 280 Btu/lb of fermentable sugar converted.

Assuming a square fermenting tank 13 ft per side to hold a brew of 500 bbl and allowing 1 ft between the tank wall and the attemperator for easy cleaning, an 11 ft^2 attemperator can be used, giving 44 feet of tubing.

From Figure 2, the maximum daily conversion rate is 7 lb/bbl. Calculating for 500 bbl per day at 280 Btu/lb of sugar converted,

$$7 \times 500 \times 280 = 980{,}000 \text{ Btu/day or } 40{,}833 \text{ Btu/h}$$

Assuming a 50°F fermenting beer temperature and 20°F brine (a temperature difference of 30°F) and a heat transfer rate of 15 $\text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$ for the attemperator, the surface area required is

$$40{,}833/(15 \times 30) = 90.7 \text{ ft}^2$$

Considering 4 in. OD tubing with an external area of 1.05 ft^2/ft, the length required is

$$90.7/1.05 = 86.4 \text{ ft}$$

Two attemperators (each 11 ft square) give 88 ft of tubing, which is adequate for the conditions outlined.

Old attemperators usually consisted of one or more rings of 3 or 4 in. copper or stainless tubing, concentric with the walls of the tank and supported at about two-thirds of the height of the liquid. Almost all modern fermenter designs use exterior jackets for temperature control. The side wall of the fermenter may have two or three individual jackets and the cone or bottom of vertical fermenters may also have one or two small jackets. Each jacket uses a baffled flow or dimple plate design that maintains good flow and good heat transfer across all areas of the jacket. A glycol solution or liquid ammonia may be circulated through the cooling jackets. These tank changes, dictated by automation and economics, allow easier in-place tank cleaning and provide more cooling effect in fermenting.

Stock Cellar

The stock cellar may be a refrigerated room containing storage tanks that do not have any cooling capacity, or it may be an ambient room containing storage tanks with exterior jackets or interior cooling surfaces. Cooled beer from fermentation is transferred into these tanks for aging or maturing, as the process is sometimes called. Some brewers prefer some yeast carry-over into aging, so they simply transfer the fermented beer into the stock cellar tanks. Other brewers do not want as much (or perhaps no) yeast carry-over. Storage residence time varies, depending on the wishes of the brewer. Typical residence times for modern breweries range from 5 to 15 days, but much longer times may be used. Under cold-storage conditions, slow, subtle chemical changes take place that are very important to the final flavor and aroma profile of the beer or ale. Physical changes, such as precipitation of insoluble proteins, also occur. These changes are important for preventing haze formation in the finished product.

Modern aging tanks are normally pressurized with carbon dioxide to prevent air from coming into contact with the aging beer. For stock cellars that use storage tanks that are vented to the atmosphere, adequate provision must be made to supply fresh air in sufficient amounts to keep the CO_2 concentration below 0.5%. Air-conditioning equipment, using chemical dehumidification and refrigeration, is generally used to maintain dry conditions such as 32°F and 50% rh in storage areas. This decreases mold growth and rusting of steel girders and other steel structures. To maintain lower CO_2 concentration in tightly closed cellars and to reduce operational cost, heat exchange sinks and thermal wheels are used to cool incoming fresh air and to exhaust cold stale air.

Air compressor systems commonly use air driers with refrigerated aftercoolers, 32°F glycol coolers, desiccant drying, or a combination. This is necessary if lines pass through areas below 32°F.

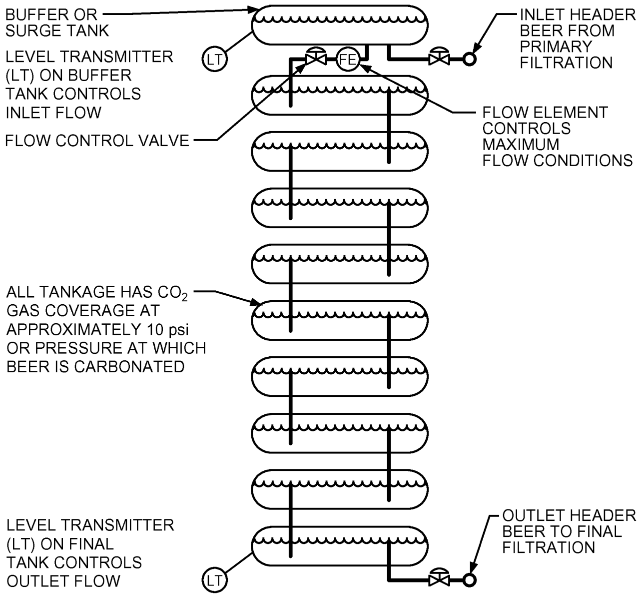


Fig. 3 Continuous Aging Gravity Flow

A continuous aging process used in multistory buildings, all gravity flow, is shown in Figure 3. The process is better for larger operations that principally produce one brand of beer.

Kraeusen Cellar

Instead of carbonating the beer during the finishing step, some brewers prefer to carbonate by the Kraeusen method. In this procedure, fully fermented beer is moved from the fermenting tank to a tank capable of holding about 20 psig. A small percentage of actively fermenting beer is added. The tank is allowed to vent freely for 24 to 48 h, then is closed and the CO_2 pressure allowed to build. Because the amount of CO_2 retained in the beer is a function of temperature and pressure, the brewer can achieve the desired carbonation level by controlling either or both pressure and temperature. After Kraeusen fermentation, generally a week or more, the beer may be moved to another storage tank. However, the brewer can accomplish the same effect by leaving the beer in the Kraeusen tank and cooling the beer by space cooling, tank coils, or both.

Heat is generated by this secondary fermentation, but the temperature of the liquid does not rise as high as it did in the fermenter because fermentable sugars are only available from the small percentage of actively fermenting beer, added as Kraeusen. Furthermore, the bulk of the liquid may have a lower starting temperature than in primary fermentation. Typically, a temperature of 40 to 50°F may be reached at the peak, after which the liquid cools to the ambient temperature of the room. This cooling can be accelerated in the tanks by circulating a cooling liquid, such as propylene glycol, through attemperators. Because heat is generated during Kraeusen fermentation, refrigeration load calculations must include removal of this heat by transfer to air in the cellar, by tank coils, or by a combination of both. Furthermore, if the tank is to be used as a storage tank, the calculation must include the necessary heat removal to reduce the beer temperature to the desired level.

Finishing Operations

After flavor maturation and clarification in the storage tanks, the beer is ready for finishing. Finishing includes carbonation, stabilization, standardization, and clarification.

Carbonation. Any of the following processes are used to raise the CO_2 concentration from 1.2 to 1.7 volumes/volume to about 2.7 volumes/volume:

- Kraeusen
- In-line
- In-tank with stones
- Saturator
- Aging train

Stabilization. The formation of colloidal haze, caused by soluble proteins and tannins forming insoluble protein/tannin complexes, is reduced by any of the following materials:

- Enzymes (papain)
- Tannic acid
- Tannin absorbents
- Protein absorbents, silica gel, bentonite

Standardization. Chilled, deaerated, and carbonated water is added to adjust original gravity from high-gravity level (14 to 16° Brix) down to normal package levels (10 to 12° Brix or lower for low-calorie beer).

Clarification. In the finishing cellar, beer is polished by filtration and is then carbonated by any of several methods. Filtering is normally done with an easily automated diatomaceous earth (DE) filter. Some cellulose pulp filters and sheet filters are still used, but they require more labor. After the filtration step, frequently a cartridge-type filter will be used to trap any particles that may still be present. Recently, various types of cartridges and membranes have been used to produce products that are essentially sterile. The number of filters used depends on the brilliance desired in the finished product. After this final processing, beer is transferred to the government cellar and held until it is needed for filling kegs in the racking room or bottles or cans in the packaging plant. In some breweries, initial clarification is accomplished using centrifuges. This reduces the load on the filtration system, allowing higher flow rates and longer filter runs.

Outdoor Storage Tanks

Some breweries use vertical outdoor fermenting and holding tanks (similar to those popular with dairies). These tanks have working capacities of 2000 to 10,000 barrels. The geometry of these tanks includes a conical bottom and height-to-diameter ratios from 1:1 to 5:1. The tanks are jacketed and use propylene glycol or the direct expansion of ammonia for cooling. Insulation is usually 4 to 6 in. thick polyurethane foam with a stainless steel cladding. They may be built as fermenters or as aging tanks, or in many cases, the same tank may serve for both fermenting and aging, with no beer transfer.

Hop Storage

If raw hop cones are used, they should be stored at a temperature of 32 to 34°F with 55 to 65% rh and very little air motion to prevent excessive drying. Sweating of the bales should not be permitted because this would carry off the light aromatic esters and deteriorate the fine hop character. Nothing else should be stored in the hops cellar because foreign odors may be absorbed by the hops, which would result in off-flavors in the beer. Hops pellets are packed in airtight, sealed containers, but should be stored near or below 32°F to prevent flavor and aroma deterioration. Hop extracts are generally very stable and may be stored at ambient temperatures.

Yeast Culture Room

In the yeast culture room, yeast is propagated to be used in reseeding and replacing yeast that has lost its viability. Normal fermentation of aerated wort also propagates yeast. The amount of yeast roughly triples during fermentation, depending on the degree of aeration. A portion of this yeast is repitched (reused) in later fermentation, and the balance is discarded as waste yeast, which is sometimes sold for other purposes. Clean yeast, usually the middle layer of the yeast deposit that remains in a fermenting tank after removal of the beer, is selected for repitching.

Repitched yeast is carefully handled to avoid contamination with bacteria and is stored in the yeast room as a liquid slurry (yeast balm) in suitable vats. If open vats are used, 80% rh is required to prevent the yeast from hardening on the vat walls. The CO_2 blanket on top of the vats should not be disturbed by excessive air motion. There is considerable variation in yeast handling and recycling practices.

PASTEURIZATION

Plate pasteurizers heat beer to a temperature sufficient for proper pasteurization (15 s at 160°F or 10 s at 165°F) and then cool the pasteurized product with incoming cold beer. Plate pasteurizers and microfiltration are used to produce a beer that is similar to draft beer but does not require refrigeration to prevent spoilage. It is distributed in bottles and cans that can be of slightly lighter construction because they do not have to withstand the high pressure created in tunnel pasteurizers.

CARBON DIOXIDE

The amount of CO_2 produced per barrel of wort depends on the original gravity (starting sugar concentration) and the final gravity of the beer (ending sugar concentration). Depending on the type of fermenter and amount of free head space at the start of fermentation, over 75% of this gas may be collected, purified, and liquefied for later use in the brewery. In addition to carbonating the beer to the proper level, CO_2 is also used to purge air from tanks, to push beer from one tank to another, for pressure in tanks of beer, and for operating bottle, can, and keg lines.

Decades ago, open-top fermenters were common. Carbon dioxide from fermentation filled the fermenting room and was a serious health hazard. Concentrations below 0.5% were generally considered to be safe for the operators, but higher concentrations reduced a worker's efficiency. Concentrations between 4 and 5% were considered too dangerous to work in for more than a minute or two. Because carbon dioxide is heavier than air, it tends to settle to the floor. Fermenting rooms were constructed with outlets near the floor where the elevated concentrations of carbon dioxide could be withdrawn. Fresh air inlets were located at the upper levels of the room.

Almost all modern breweries now use fully closed fermentation tanks. Not only do these closed tanks protect the process from accidental contamination, but all carbon dioxide can be either vented outside of the room, or directed to a collection system. As federal and state regulation became more common, very strict safety standards were adopted for exposure to carbon dioxide in the working areas. To comply with these standards and avoid potential penalties from agencies such as the Occupational Safety and Health Administration (OSHA), many modern breweries now use monitoring systems to detect elevated concentrations of carbon dioxide in the various enclosed work areas in the brewery.

Collection

Carbon dioxide gas, produced as a by-product of fermentation, can be collected from closed fermenters, compressed, and stored in pressure tanks for later use. It may be used for final carbonation, counterpressure in storage and finishing tanks, transfer, and bottling and canning. In the past, the CO_2 was stored in the gaseous state at about 250 psig. Today, however, in most medium and large breweries, the gas is collected and, after thorough washing and purification, it is liquefied and stored. Carbon dioxide stored in the liquid state occupies about 2% of the volume of an equal mass of gas at the same pressure at room temperature.

As an example, from each barrel of wort fermented, about 13 lb of CO_2 is generated over a period of five days, though not at a constant daily rate. Therefore, brews must be carefully scheduled to provide the necessary CO_2 gas, thereby minimizing storage requirements. As a general rule, only about 50 to 60% of the total gas generated is collected. Gas generated at the beginning and end of the fermentation cycle is discarded because of excessive air content and other impurities.

From the fermenting tank, the gas is piped through a foam trap to a gas pressure booster. Surplus gas is discharged to the outside from a water-column safety relief tank, which also protects the fermenting tank from excessive gas pressure. To compensate for friction pressure loss in the long lines to the compressor and to increase its capacity, the booster raises the pressure from as low as 1 in. of water to 5 or 6 psig.

Compressors, which in the past were two-stage with water injection, are being replaced by nonlubricated compressors that use carbon or nonstick fluorocarbon rings. Today, lubricated screw and reciprocating compressors are used for food and beverage-grade CO_2 production in commercial CO_2 plants and in some large breweries. These may be single two-stage compressors or two compressors comprising individual high and low stages. A complete collection system consists of suction and foam trap; rotary boosters, where required; scrubber; deodorizer; compressor (or compressors); intercoolers and aftercoolers; dehumidifying tower; condenser (with refrigeration from a separate system to ensure that no CO_2 enters the main system through leaks); liquid storage tanks; and vaporizers, all interconnected and automatically controlled.

Liquefaction

The condensing pressures of carbon dioxide at several temperatures are

–20°F	200 psig
–14°F	225 psig
–8°F	252 psig

The latent heat at saturation temperature is about 120 Btu/lb. The refrigerant for liquefying the compressed gas should be about –21°F to condense the CO_2 effectively. Most of the moisture must be removed from the compressed gas; this may be done by passing the gas through a horizontal-flow finned coil (located in a 36°F cellar), which condenses out about 80% of the moisture (i.e., the condensate is drained from the system). Also, this is done effectively with refrigerant-cooled precoolers, intercoolers, and aftercoolers. Sending the gas through desiccant driers removes additional moisture. The emerging gas has a slightly higher temperature, but has a dew point around –70°F or lower.

Under these conditions, gas is liquefied when it comes in contact with the liquefying surfaces, which stay ice-free because of the low moisture content (–40°F dew point) of the gas, thus ensuring continuous service. Dryers are installed in duplicate with automatic timing for regeneration of the desiccant material. Desiccant dryers usually rely on heated CO_2 as the regeneration gas. An earlier method used dual sets of double-pipe dryers, which froze out moisture and retained it in the heat exchanger.

Liquefiers are vertical shell-and-tube, inclined double-pipe, or shell-and-tube types. The refrigerant side is operated fully flooded, with refrigerant supplied from a system separate from the main system. Carbonating systems have changed with all-closed fermenters, refrigerated condensing systems, and large liquid CO_2 holding tanks. See Figure 4 for collecting and liquefaction system flow diagrams.

CO_2 Storage and Reevaporation

Condensed CO_2 drains into a storage tank, which is usually designed for a working pressure of 300 psig and varying storage capacities of 10,000 to 120,000 lb each. The vessel is insulated and is equipped with equalizing connections, safety valves, liquid-level indicators, and electric heating units. Gas purity tests are regularly conducted from samples withdrawn from above the liquid level.

As liquid is withdrawn from the tank, it is introduced to a steam-heated liquid vaporizer, which is automatically controlled to give the desired superheat to the vaporized gas. This type of vaporizer is now replacing other types because of its ability to control the temperature of CO_2 gas. Vaporized gas is directed to large, high-pressure surge tanks, where the pressure may be over 200 psig. Carbon dioxide from these surge tanks passes through pressure reduction valves to supply the brewery with gas that normally ranges from 80 to 100 psig.

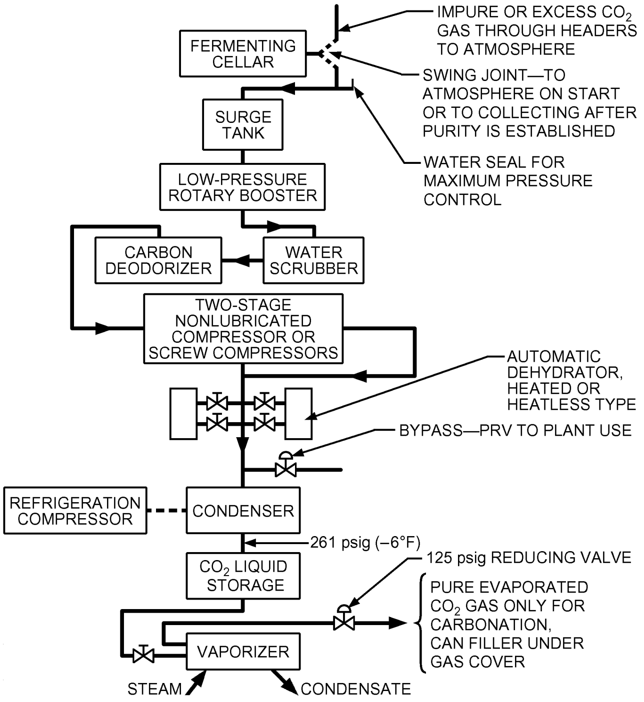


Fig. 4 Typical Arrangement of CO_2 Collecting System

HEAT BALANCE

Most of the steam required for processing, heating water, and general plant heating can be obtained as a by-product. Because the manufacture of beer is a batch process with various peaks occurring at different times, the study of the best heat balance possible is difficult. In a given plant, it depends on many variables, and a comprehensive study of all factors is necessary.

In brewery plant locations where electric energy costs are high, installation of cogeneration facilities can be favorable. However, in plants that produce in excess of 3 million bbl annually, the steam turbine as a prime mover often comes into prominence. A bleeder steam turbine operating at 400 psig can be used to drive a refrigeration compressor, electrical generator, or both; steam bled from it can be used for process and other needs requiring low-pressure steam. In smaller plants, less favorable heat balances must be accepted in line with more economical plant investment programs. Each brewery requires individual study to develop the most economical program.

Many process steam loads are highly variable; for example, the brew kettle's warm-up cycle (both equipment mass and the content's mass) requires three to five times as much steam as brewing does. Steam plant (boiler) sizing is significantly affected by this changeability. Initial boiler size/capacity can be reduced by installing a heat storage tank (e.g., for brewing water) that can be heated over a longer period of time, thus reducing the dynamic peak load required at batch start-up.

COMMON REFRIGERATION SYSTEMS

Absorption Machine for Heat Balance (especially for air conditioning and water cooling for wort cooling). The unit requires a careful heat balance study to determine whether it is economical. These machines may be a good selection if excess 20 psig steam (single-effect) or 110 psig steam (double-effect) is available.

Halocarbon Refrigerant Cascade System. Oil-free ammonia as brine can be pumped at a 1:1 ratio with water. The ratio of motive power to refrigeration at 25 and 185 psig is 1.4 bhp/ton.

Direct Centrifugal. This is often an oil-free ammonia system with a 1:1 ratio with water. The unit requires pumps. This is usually the most expensive and least efficient of these systems.

Oil-Sealed Screw Compressors. Ammonia is circulated at a 1:1 ratio in this system. The units require pumps. The ratio of motive power to refrigeration is 1.26 bhp/ton. This is probably the least expensive system.

Oil-Free Compressors, Screw Type. The ratio of motive power to refrigeration is 1.5 bhp/ton. System noise levels can be high.

Large Balanced Opposed Horizontal Double-Acting Reciprocating Compressor. While the system is not oil-free, good oil separation equipment minimizes this problem. It can use recirculation or direct expansion. The ratio of motive power to refrigeration is 1.25 bhp/ton. This system requires the most maintenance, and can be the most expensive.

Further automation has been accomplished by programming the flow of materials in the brewhouse, as well as the entire brewing operation. The newest brewing operations are fully automated.

Where necessary, a cooling tower may be used to reduce thermal pollution or to conserve water in the pasteurizing phase. Ecology plays an important part in the brewery; stacks are monitored for particulates, effluent is checked, and heat from kettle vents and others is recovered. Water use is more closely regulated, and refrigeration systems use water-saving equipment, including evaporative condensers.

Food-Grade Brines. Some of the cooling temperatures (e.g., ingredient water required for finished product mixing from heavy-gravity brewing) are near freezing, thus requiring coolant temperatures below freezing and consequently the necessary brine in the coolant. In food and beverage facilities, this brine should be food-grade propylene glycol so that minor leaks (e.g., heat exchanger pinholes) into the ingredient will not render the finished product nonsalable. If other plant systems require brine solutions, they should also use food-grade propylene glycol to eliminate the chance of injecting a non-food-grade brine into a food-grade system.

VINEGAR PRODUCTION

Vinegar is produced from any liquid capable of first being converted to alcohol (e.g., wine, cider, malt) and syrups, glucose, molasses, and the like.

First Stage: Conversion of sugar to alcohol by yeast (anaerobic)

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$$

Second Stage: Conversion of alcohol to acetic acid by bacterial action (aerobic)

$$CH_3CH_2HO + O_2 \rightarrow CH_3COOH + H_2O$$

Bacteria are active only at the surface of the liquid where air is available. Two methods are used to increase the air-to-vinegar surface:

The **packed** (or **Frings**) **generator** is a vertical cylinder with a perforated plate and is filled with oak shavings or other inert support material intended to increase column surface area. The weak alcohol and vinegar culture are introduced, and the solution is continuously circulated through a sparger arm, with air introduced through drilled holes in the top of the tank. A heat exchanger is used to remove the heat generated and to maintain the solution at 86°F. This is a batch process requiring 72 h.

In **submerged fermentation**, air is distributed to the bacteria by continuously disbursing air bubbles through the mash in a tank filled with cooling coils to maintain the 86°F temperature. This also is a batch process, requiring 39 h.

Concentration is best accomplished by removing some of the water in the form of ice, which increases the acid concentration by 12 to 40%. In freezing out water, a rotator is often used. About 0 to 10°F is required on the evaporating surface to produce the best crystals; the ice is separated in a centrifuge. The vinegar is then stored 30 days before filtering. Effective concentration can also be achieved by distillation (as is done for distilled white vinegar).

WINE MAKING

The use of refrigeration to control the rates of various physical, chemical, enzymatic, and microbiological reactions in commercial wine making is well established. Periods at elevated temperatures, followed by rapid cooling, can be used to denature oxidative enzymes and proteins in grape juices, to retain desirable volatile constituents of grapes, to enhance the extraction of color pigments from skins of red grapes, to modify the aroma of juices from certain white grape cultivars, and to inactivate the fungal populations of mold-infected grapes. Reduced temperatures can slow the growth rate of natural yeast and of the enzymatic oxidation of certain phenolic compounds, assist in the natural settling of grape solids in juices, and favor the formation of certain by-products during fermentation. Also, reduced temperatures can be used to enhance the nucleation and crystallization of potassium bitartrate from wines, to slow the rate of aging reactions during storage, and to promote the precipitation of wood extractives of limited solubility from aged brandies.

The extent to which refrigeration is used in these applications depends on such factors as the climatic region in which the grapes have been grown, the grape cultivars used, the physical condition of the fruit at harvest, the styles and types of wines being produced, and the discretion of the winemaker.

Presently, the wine industry in the United States is heavily committed to the production of table wines (ethanol content less than 14% by volume). Considerably less emphasis is being placed on the production of dessert wines and brandies than in the past. Additionally, the recent growth in wine cooler popularity has significantly altered winery operations where they are produced. A variety of enological practices and winery equipment can be found between the batch emphasis of small wineries (crushing tens of tons per season) and the continuous emphasis of large wineries (crushing hundreds or thousands of tons per season).

The applications of refrigeration will be classified and considered in the following order:

1. Must cooling
2. Heat treatment of red musts
3. Juice cooling
4. Heat treatment of juices
5. Control of fermentation temperature
6. Potassium bitartrate crystallization
7. Control of storage temperatures
8. Chill-proofing of brandies

MUST COOLING

Must cooling is the cooling of crushed grapes before separating the juice from the skins and seeds. White wine grape musts will often be cooled before being introduced to a juice-draining system or a skin-contacting tank; this is done to reduce the rate of oxidation of certain juice components, as well as to prevent the onset of spontaneous fermentation by wild and potentially undesirable organisms. Must cooling can be used when grapes are delivered to the winery at excessively high temperatures or when they have been heated to aid in pressing or extracting red color pigments.

In general, tube-in-tube or spiral heat exchangers are used. Tubes of at least 4 in. internal diameter with detachable end sections of large-radius return bends are necessary to reduce the possibility of blockage by any stems that might be left in the must after the crushing-destemming operation. The cooling medium can be chilled water, a glycol solution, or a directly expanding refrigerant. Overall heat transfer coefficients for must cooling range between 70 and 125 $Btu/h \cdot ft^2 \cdot °F$, depending on the proportions of juice and skins, with the must side providing the controlling resistance. In small wineries, jacketed draining tanks and fermenters are often used to cool musts in a relatively inefficient batch procedure in which the overall coefficients are on the order of 1.70 to 5.30 $Btu/h \cdot ft^2 \cdot °F$ because the must is stationary and, therefore, rate-controlling.

HEAT TREATMENT OF RED MUSTS

Most red grapes have white or greenish-white flesh (pulp) and juice. The coloring matter or pigments (anthocyanins) reside in the skins. Color can be rapidly extracted from these varieties by heat treating musts so that the pigment-containing cells are disrupted before actual fermentation. This process is done in several countries throughout the world when grape skins are low in color or when color extraction during fermentation is poor. Must heating is necessary to produce the desirable flavor profile of some varieties, most notably Concord, when manufacturing juices, jellies, and wines. The series of operations is referred to as thermovinification. The must is heated to temperatures in the range of 135 to 167°F, generally by draining off some of the juice, condensing steam, and returning the hot juice to the skins for a given contact time, often 30 min. The complete must can be cooled prior to separation and pressing, or the colored juice can be drawn off and cooled prior to the fermentation.

Heat treatment can also be used to inactivate the more active oxidative enzymes found in red grapes infected by the mold *Botrytis cinerea*. It can further aid the action of pectic enzyme preparations added to facilitate pressing of some cultivars. In all cases, the temperature/time pattern used is a compromise between desirable and undesirable reactions. The two most undesirable reactions are caramelization and accelerated oxidation of the juice. Condensing steam and tube-in-tube exchangers are generally used for these applications, with design coefficients similar to those given previously for must cooling.

JUICE COOLING

Juices separated from the skins of white grapes are usually cooled to between 35 and 70°F to aid natural settling of suspended grape solids, to retain volatile components in the juice, and to prepare it for cool fermentation. Tube-in-tube, shell-and-tube, and spiral exchangers and small jacketed tanks are used with either direct expansion refrigerant, propylene glycol solution, or chilled water as the cooling medium. Overall coefficients for juice cooling range between 95 and 150 $Btu/h \cdot ft^2 \cdot °F$ for the exchanger and 4.40 to 8.80 $Btu/h \cdot ft^2 \cdot °F$ for small jacketed tanks.

The small jacketed tank values can be improved significantly by juice agitation. Transport and thermal properties of 24% (by mass) sucrose solutions can be used for grape juices. There is a general tendency for medium and large wineries to use continuous-flow juice cooling arrangements of jacketed tanks.

HEAT TREATMENT OF JUICES

Juices from sound grapes can be exposed to a high-temperature, short-time (HTST) treatment to denature grape proteins, reduce the number of unwanted microorganisms, and, some winemakers believe, enhance the varietal aroma of certain juices. Denaturation of proteins reduces the need for their removal (by absorptive clays such as bentonite) from the finished wine. However, turbid juices and wines can result from this treatment, presumably because of modification of the pectin and polysaccharide fraction. Clarified juices from mold-infected grapes can be treated in a similar way to denature oxidative enzymes and to inactivate the molds. Most wineries in the United States rely on "pure culture" fermentation to achieve consistently desirable results; hence the value of HTST treatment in the control of microbial populations.

A typical program includes rapidly raising the juice temperature to 194°F, holding it for 2 s, and rapidly cooling it to 60°F. Plate heat exchangers are used because of their thin film paths and high overall coefficients. Grape pulp and seeds can cause problems in this equipment if they are not completely removed beforehand.

FERMENTATION TEMPERATURE CONTROL

Anaerobic conversion of grape sugars to ethanol and carbon dioxide by yeast cells is exothermic, although the yeast is capturing a significant quantity of the overall energy change in the form of high-energy phosphate bonds. Experimental values of the heat of reaction range between 79.3 and 95.3 Btu/mole, with 94.4 Btu/mole being generally accepted for fermentation calculations (Bouffard 1985).

One gallon of juice at 16.37 lb/ft^3 sucrose (24° Brix) will produce approximately 60 gal of carbon dioxide during fermentation. Allowing for the enthalpy lost by this gas, with its saturation levels of water and ethanol vapors, the corrected heat release value is 90.9 Btu/mole at 59°F and 83.6 Btu/mole at 77°F. The adiabatic temperature rise of the 16.37 lb/ft^3 juice would then be 87°F, based on the 59°F value, and 82°F, based on the 77°F value. Whether a fermentation approaches these adiabatic conditions depends on the difference between the rate of heat generation by fermentation and the rate of heat removal by the cooling system. For constant-temperature fermentations, which are the most common type of temperature control practiced, these rates must be equal. Red wine fermentations are generally controlled at temperatures between 75 and 90°F, whereas white wines are fermented at 50, 60, or 68°F, depending on the cultivar and type of wine being produced. The more rapid fermentations of red wines are used in the cooling load calculations of individual fermenters; a more involved composite calculation, allowing for both red and white fermentations staggered in time, is necessary for the overall daily fermentation loads.

At 68°F, red wines have average fermentation rates in the range of 2.5 to 3.1 lb/ft^3 per day, which correspond to heat release rates of approximately 21 to 26 Btu/ft^3 per hour. The peak fermentation rate is generally 1.5 times the average, leading to values of 31.5 to 39.0 Btu/ft^3 per hour. This value, multiplied by the volume of must fermenting, provides the maximum rate of heat generation. The heat transfer area of the jacket or external exchanger can then be calculated from the average coolant temperature and overall heat transfer coefficient.

The largest volume of a fermenter of given proportions, with fermentation that can be controlled by jacket cooling alone, is a function of the maximum fermentation rate and the coolant temperature. The limitation occurs because the volume (and hence the heat generation rate) increases with the diameter cubed, whereas the jacket area (and hence the cooling rate) only increases with the diameter squared. Similarly, the temperature rise in small fermenters, cooled only by ambient air, depends on the fermenter's volume and shape and the ambient air temperature (Boulton 1979a).

Development of a kinetic model for wine fermentations (Boulton 1979b) has made it possible to predict the daily or hourly cooling requirements of a winery. The many different fermentation temperatures, volumes, and starting times can now be incorporated into algorithms that predict future demands and schedule off-peak electricity usage, allowing for optimal control of refrigeration compressors.

POTASSIUM BITARTRATE CRYSTALLIZATION

Freshly pressed grape juices are usually saturated solutions of potassium bitartrate. The solubility of this salt decreases as alcohol accumulates, so newly fermented grape wines are generally supersaturated. The extent of supersaturation and even the solubility of this salt depend on the type of wine. Young red wines can hold almost twice the potassium content at the same tartaric acid level as young white wines, with other effects caused by pH and ethanol concentration. Because salt solubility also decreases with temperature, wines will usually be cold-stabilized so that crystallization occurs in the tank rather than in the bottle if the finished wine is chilled. In the past, this was done by holding the wine close to its congealing temperature (usually 25 to 21°F for table wines) for two to three weeks. Crystallization at these temperatures can be increased dramatically by introduction of nuclei, either potassium bitartrate powder or other neutral particles, and subsequent agitation. In modern wineries, it is particularly important to supply nuclei for crystallization, because unlike older wooden cooperage, stainless steel tanks do not offer convenient sites for rapid growth. Holding times can be reduced to 1 to 4 h by these methods. Several continuous and semicontinuous processes have been developed, most incorporating an interchange of the cold exit stream with warmer incoming wine (Riese and Boulton 1980). Dessert wines can be stabilized in the same manner, except that the congealing temperatures are usually in the range of 12 to 7°F. In all wines, it is usual for stabilization to occur sometime after grape harvest and for suction temperatures of the refrigeration compressors to be adjusted in favor of low coolant temperatures rather than refrigeration capacity.

STORAGE TEMPERATURE CONTROL

Control of storage temperature is perhaps the most important aspect of postfermentation handling of wines, particularly generic white wines. Transferring wine from a fermenter to a storage vessel generally results in at least a partial saturation with oxygen. The rates at which oxidative browning reactions (and the associated development of acetaldehyde) advance depend on the wine, its pH and free sulfur dioxide level, and its storage temperature. Berg and Akiyoshi (1956) indicate that, in oxidation of white wines, for temperatures below ambient, the rate was reduced to one-fifth its value for each 18°F reduction in temperature. Similar studies of hydrolysis of carboxylic esters (Ramey and Ough 1980) produced during low-temperature fermentations indicate that the rate was more than halved for each 18°F reduction in temperature. These latter data suggest that, on average, the esters have half-lives of 380, 600, and 940 days when wine is stored at 60, 50, and 40°F, respectively. As a result, wines should generally be stored at temperatures between 40 and 50°F if oxidation and ester hydrolysis are to be reduced to acceptable levels. The importance of cold bulk wine storage will likely increase as vintners strive to reduce the amount of sulfur dioxide used to control undesirable yeasts.

Cooling requirements during storage are easily calculated using the vessels' dimensions and construction materials as well as the thickness of the insulation used.

CHILL-PROOFING BRANDIES

In brandy production, refrigeration is used in the chill-proofing step, just before bottling. When the proof is in the range of 100 to 120 (50 to 60% v/v ethanol), aged brandies contain polysaccharide fractions extracted from the wood of the barrels. When the proof is reduced to 80 for bottling, some of these components with limited solubility become unstable and precipitate, often as a dispersed haze. These components are removed by rapidly chilling the diluted brandy with a plate heat exchanger to a temperature in the 0 to 32°F range and filtering while cold with a pad filter. The outgoing filtered brandy is then used to precool the incoming stream, thus reducing the cooling load. Calculations can be made by using the properties of equivalent ethanol/water mixtures, with particular attention to the viscosity effects on the heat transfer coefficient.

CARBONATED BEVERAGES

Refrigeration equipment is used in many carbonated beverage plants. The refrigeration load varies with plant and production conditions; small plants may use 150 tons of refrigeration and large plants may require over 1500 tons.

Dependency on refrigeration equipment has diminished in carbonated beverage plants using modern deaerating, carbonating, and high-speed beverage container-filling equipment. In facilities that use refrigeration, product water is often deaerated before cooling to aid carbonation. In addition, cooling the product at this stage of production (1) facilitates carbonation to obtain maximum stability of the carbonated beverage during filling (reduces foaming), (2) permits reducing the pressure at which the beverage is filled into the container (minimizing glass bottle breakage at filler), and (3) reduces overall filling equipment size and investment.

Immediately before filling, beverage product preparation requires the use of equipment for proportioning, mixing, and carbonating so that the finished beverage has the proper release of carbon dioxide gas when it is served. The equipment for these functions is frequently found as an integrated apparatus, often called a mixer-carbonator or a proportionator.

Table 2 lists the volume of carbon dioxide dissolved per volume of water at various temperatures. At 60°F and atmospheric pressure, a given volume of product water will absorb an equal volume of carbon dioxide gas. If the carbon dioxide gas is supplied to the product water under a pressure of approximately 15 psig (interpolating between 10 and 20 psig), it will absorb two volumes. For each additional 15 psig, one additional volume of gas is absorbed by the water. Reducing the temperature of the product water to 32°F increases the absorption rate to 1.7 volumes. Therefore, at 32°F product temperature, each increase of 15 psig in CO_2 pressure results in the absorption of an additional 1.7 volumes instead of one volume as when the product water temperature is 60°F. Carbonated levels for different products vary from less than 2.0 volumes to around 5.0 volumes.

Table 2 Volume of CO_2 Gas Absorbed in One Volume of Water

Temperature °F	Pressure in Bottle, psig										
	0	10	20	30	40	50	60	70	80	90	100
32	1.71	2.9	4.0	5.2	6.3	7.4	8.6	9.7	10.9	12.2	13.4
40	1.45	2.4	3.4	4.3	5.3	6.3	7.3	8.3	9.2	10.3	11.3
50	1.19	2.0	2.8	3.6	4.4	5.2	6.0	6.8	7.6	8.5	9.5
60	1.00	1.7	2.3	3.0	3.7	4.3	5.0	5.7	6.3	7.1	7.8
70	0.85	1.4	2.0	2.5	3.1	3.7	4.2	4.8	5.4	6.1	6.6
80	0.73	1.2	1.7	2.2	2.7	3.2	3.6	4.1	4.6	5.2	5.7
90	0.63	1.0	1.5	1.9	2.3	2.7	3.2	3.6	4.0	4.5	4.9
100	0.56	0.9	1.3	1.7	2.0	2.4	2.8	3.2	3.5	3.9	4.3

BEVERAGE AND WATER COOLERS

The main sanitation requirements for beverage and/or water coolers are hygiene and ease of cleaning, particularly if the beverage is cooled rather than the water. The key point is that water freezes easily, and cooler equipment design needs to avoid this. The early Baudelot tank solved the problem by not forming ice; however, because sanitation of such systems is a problem, their use is not recommended.

If a cooler is needed, most plants choose plate heat exchangers and careful control of temperature. Plate heat exchangers reduce ice formation through high turbulence, which reduces thermal gradients. Furthermore, they are hygienic and easy to clean. These heat exchange devices are normally fed by a brine (not direct refrigeration) and are protected against brine leakage, for example, by ensuring that the brine pressure is lower than the beverage product/water pressure.

Many beverage plants use coolers with patented direct-expansion refrigeration equipment to achieve system security, hygiene, ease of cleaning, etc., using a Baudelot-type system. However, this equipment is only used for cooling water (not product), making it easier to clean. This is achieved by the equipment manufacturer's long experience with a proprietary system and its attention to detailed equipment design.

When coolers are necessary, it is recommended that this component of the refrigeration system be located adjacent to, or integrated with, the proportioner-mixer-carbonator. Usually these devices are physically positioned next to the beverage container filler. Normally, the refrigeration plant itself should be housed separately from product processing and filling areas, preferably located together with the other plant utilities (boilers, hot water heater, air compressors, etc.).

It is most important to keep the beverage free from contamination by foreign substances or organisms picked up from the atmosphere or from metals dissolved in transit. Consequently, coolers are designed for easy cleaning and freedom from water stagnation. The coolers and product water piping are fabricated of corrosion-resistant nontoxic metal (preferably stainless steel); however, certain plastics are usable. For example, acrylonitrile-butadiene-styrene (ABS) is used in the beverage industry for raw water piping.

Refrigeration Plant

Halogenated hydrocarbons or ammonia refrigerants are commonly used for plants requiring beverage product and/or water coolers. Refrigeration compressors vary from two-cylinder vertical units to larger, multicylinder V-style compressors.

The refrigeration plant should be centralized in larger production facilities. With the multiplicity of product sizes, production speeds, and other factors affecting refrigeration load, an automatically controlled central plant conserves energy, reduces electrical energy costs, and improves opportunities for a preventive maintenance program.

Makeup water and electrical energy costs encourage careful selection and use of compressors, air-cooled condensers, evaporative condensers, and cooling towers. Some plants have economized by using spent water from empty can and bottle rinsers as makeup water for evaporative condensers and cooling towers. Also, thermal storage (e.g., cold glycol storage tanks) can be used to reduce refrigeration equipment size.

As indicated earlier, the temperature to which the product must be cooled depends on the type of filling machinery used, as well as the deaerating-mixing-proportioning-carbonating equipment used. Cooling needs may be divided into three general categories: those that use water (1) at supply temperature or less, (2) at 45 to 55°F, and (3) at 40°F or lower. The exact temperature to which the product should be cooled depends on the specific requirements of the beverage product and the needs of the particular plant. These requirements are primarily based on product preparation, production equipment availability, and capital costs versus operating costs.

The refrigeration load per case has been reduced by improved filling technology. Fill temperatures between 58 and 60°F have been achieved, which raises the required coolant temperature (thus raising refrigerant suction temperatures and lowering compressor power input).

Refrigeration Load

Refrigeration load is determined by the amount of water being cooled per unit of time. This is derived from the maximum fluid output of the beverage filler. Most cooling units are of the instantaneous type; they must furnish the desired output of cold water continuously, without relying on storage reserve.

Knowing the water temperature from the supply source, temperature to which the water is to be cooled, and water demand, refrigeration load can be determined by

$$q_R = Qc_p(t_s - t_c)/24$$

where

q_R = cooling load, tons of refrigeration
Q = water flow rate, gpm
t_s = supply water temperature, °F
t_c = cold-water temperature, °F
c_p = specific heat of water = 1 Btu/lb·°F

In computing the refrigeration load, one of the most troublesome values to determine is the highest temperature the incoming supply water can be expected to reach. This temperature usually occurs during the hottest summer period. Allow for additional supply water warming from flowing through piping and water treatment equipment in the beverage plant.

SIZE OF PLANT

Output of each plant depends on the beverage-filling capacity of the plant production equipment. Small, individual filling units turn out approximately 600 cases of 24 beverage containers (approximately half-pint capacity) per hour, or 240 containers per minute (cpm); intermediate units turn out up to 1200 cases per hour (480 cpm); and high-speed, fully automatic machines begin at approximately 1200 cases per hour and go through several increases in size up to the largest units, which approach 5000 cases per hour (2000 cpm).

Operation of these filling machines, which also determines demand on refrigeration machinery, usually exceeds 8 h per day, especially during summer, when market demands are highest.

An arbitrary classification of beverage plants may be (1) small plants that produce under 1.25 million cases per year, (2) intermediate plants that produce about 2.5 million cases per year, and (3) large plants that produce 15 million or more cases per year. The latter require installation of multiple-filling lines.

The usual distribution area of finished beverages is within the metropolitan area of the city in which the plant is located. Some plants have built such a reputation for their goods that they ship to warehouses several hundred miles away. Local distribution is made from there. A few nationally known products are shipped long distances from producing plants to specialized markets.

In the warehouse, cans and nonreturnable bottles filled with precooled beverage are commonly warmed to a temperature exceeding the dew-point temperature to prevent condensation and resulting package damage. Bottled goods should be protected against excessive temperature and direct sunlight while in storage and transportation. At the point of consumption, the carbonated beverage is often cooled to temperatures close to 32°F.

LIQUID CARBON DIOXIDE STORAGE

Liquefied carbon dioxide, used to carbonate water and beverages, is truck-delivered in bulk to the beverage plant. The liquid is then piped to large outdoor storage-converter tanks equipped with mechanical refrigeration and electrical heating. The typical tank unit is maintained at internal temperatures not exceeding 0°F, so that the equilibrium pressure of the carbon dioxide does not exceed 300 psig and the storage tanks need not be built for excessively high pressures. Full-controlled equipment heats or refrigerates, and safety relief valves discharge sufficient carbon dioxide to relieve excess pressure.

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