Passive conditioning of a large beverage warehouse by activating the buffer effect of the ground

Markus Gratzl^{1,*}, Markus Leeb², Thomas Reiter², and Hermann Schranzhofer³

¹ Ingenieurbüro Gratzl, Consulting Engineers, 4715 Taufkirchen, Austria

² Salzburg University of Applied Sciences, Smart Buildings and Smart Cities, 5036 Kuchl, Austria

³ Graz University of Technology, Institute of Thermal Engineering, 8010 Graz, Austria

Abstract. A new production facility for a beverage manufacturer has to provide a storage volume for around 5 million bottles as a refrigerated warehouse. The maximum temperatures were not allowed to exceed 14 °C due to the quality requirements in the production process. To achieve highest energy efficiency and to avoid year-round heating and cooling, the warehouse is passively conditioned: by explicitly coupling it with adjacent soil, its buffering effect was activated via uninsulated wall and floor components in contact with the ground. The warehouse stock was also integrated into the concept as thermal mass. Furthermore, the remaining building envelope was optimized to reduce heat gains and losses to external air to a minimum.

1 Background

The production of sparkling wine according to the centuries-old "Méthode traditionnelle" (champagne method) is characterised by the second phase of the fermentation process, which takes place as bottle fermentation. Following the alcoholic fermentation of the grape must into the base wine, this is bottled and after the actual fermentation phase, which lasts about three weeks, it is stored for at least 15 months "on the yeast" [1]. An essential factor for optimum storage during the ripening period is the storage temperature of around 10 to 12 °C. The limit value of 14 °C must not be exceeded. If this means that southern production locations (France, Spain, Italy) usually cause continuous cooling, in the temperate climate of Central Europe heating is required during winter and considerable cooling during summer.

Depending on the location, the annual average air temperature in Austria is in the range of around 8 to 10 °C – on average the best storage conditions. Due to seasonal and daily fluctuations in the outside air temperature and the influence of solar radiation, however, this potential cannot be exploited in above-ground storage areas. The situation is different for underground storage rooms: The annual mean temperature is also between 8 and 10 °C, but the influence of seasonal and daily temperature fluctuations decreases steadily with increasing depth, and the temperature amplitude decreases in the course of the year. At the

* Corresponding author: markus.gratzl@gratzl.co.at

same time, an increasing phase shift occurs with depth, as the temperature peaks in the soil occur with a delay [2].

For this reason, storage rooms have been built underground since time immemorial. One of the most common forms of application is the classic wine cellar, which until a few decades ago was also indispensable in large-scale technical wine and sparkling wine production. In recent years, however, above-ground storage facilities have increasingly gained acceptance, combining several advantages: easier accessibility without height difference to the production area, feasibility of larger storage heights, uncomplicated installation. On the other hand, there is the disadvantage of higher energy demand due to the year-round conditioning.

1.1 Hypothesis

When a leading Austrian sparkling wine producer built a new production facility, the advantages of the above-ground and cellar construction methods were to be combined. The storage capacities for around 5.5 million bottles of sparkling wine in the sparkling wine storage (3.500 m² floor space) were all to be arranged at the same level as the central production area. The above-ground construction method was intended to achieve low construction costs. The decisive difference to a conventional warehouse building were ground-coupled components completely without insulation to use the enormous thermal capacities of the adjacent soil. This, combined with the considerable thermal mass of the stored goods, meant that heating and cooling could be completely dispensed with.

However, one central question remained to be clarified: Is it possible to operate the storage areas of a large-scale champagne and sparkling wine production without active heating and cooling despite above-ground construction? Following on from this, it was also necessary to examine which thermal quality requirements had to be placed on above-ground building envelope in order to achieve the goal of natural conditioning of the storage areas.

1.2 Systematics

In comparison to conventional buildings, the solar heat gains and ventilation heat losses are (due to no windows and low ventilation needs) of very little importance for the present object. The internal heat gains are influenced by the production processes: In wine and sparkling wine halls, fermentation processes take place in large-volume production tanks, which cause heat to enter the zones. Additional heat input, especially in the wine hall, is also caused by the delivery of the grape must, which is delivered in autumn at temperatures of up to 25 °C. In contrast to this, in the sparkling wine storage only the maturation takes place in the bottles, the bottle fermentation already takes place before in an extra room (fermentation storage), from there the sparkling wine bottles are stored at a temperature of around 17 °C in the sparkling wine storage.

Additional to internal gains, transmission losses and gains on the one hand and heat storage on the other are of central importance for the heat balance. In the case of transmission, heat flows can be differentiated between above- and below-ground components. While ground-coupled components primarily serve to activate the large thermal capacity of the ground, heat losses via the rest of the building envelope can be low due to good insulation. The effect of the heat storage of the adjoining soil and the stored goods ensures that the basic principle of passive conditioning of the storage capacities shown in Fig. 1 is to function:

- In summer, heat input is temporarily compensated by the large thermal mass of the stored goods. In the longer term, the adjoining cool soil acts as a heat store where large

quantities of heat can be released. In the short term, temperature peaks of up to 14 °C are permitted.

- In winter, in addition to the already advantageous annual mean temperature of the ground of around 8 to 10 °C, the phase shift is also to be used, so that lowest ground temperatures do not occur until spring – this is when heat gains already counteract excessive cooling.

Fig. 1. Heat flows at the building in the summer (a) or winter case (b) (source: Ingenieurbüro Gratzl)

2 Methodology

In order to ensure compliance with the requirements of the storage conditions, it had to be proven that the planned concept of passive ground cooling would enable the specified limit temperatures to be permanently maintained. For this purpose, a thermal building simulation was carried out in which the consideration of three central elements was of high importance:

- a detailed soil model that not only represents a boundary condition, but also considers interaction with the heat flows to the adjoining building zones in a realistic manner and allows the input of specific soil parameters (thermal conductivity, density, specific heat, deep earth temperature)
- thermal masses within the building zone independent of the construction materials, which can be integrated into the model to varying degrees according to the occupancy of the warehouse or the production processes
- modelling of heat inputs that do not act exclusively in the building zone, but primarily directly in the thermal masses and only then secondarily in the room air

TRNSYS was used as simulation software, the coupled simulation of building, soil and thermal mass model is carried out by combining special components, the coupling of which is explained in the following sections.

2.1 Soil model

It was essential to use a sufficiently detailed soil model in order to model the problem at hand. The usual models in standards consider only a sinusoidal oscillation with a given mean temperature and amplitude [3]. Heat flows from the building to the ground arising exclusively due to the temperature difference between the two areas, but the temperature of the adjacent ground is not influenced by these heat flows. In particular this interaction and the heat propagation in the soil represent an essential prerequisite for this investigation [4]. The modelling was therefore carried out with the "TESS Basement Model" (Type 1244) [5]. Thereby, heat flows from the building into the ground via the adjacent component surfaces are simulated zone-wise in a finite element model.

2.2 Capacitance model

The filled bottles stored in lattice cages or on pallets already packed and wrapped in cartons act as thermal masses in the sparkling wine storage areas. In wine and sparkling wine halls, the insulated or uninsulated production tanks with different filling conditions must be considered. These tanks are subject to different production processes and are filled and emptied at different times of the year. The "Lump Capacitance Model" (Type 963) was used as the thermal mass model. In addition to the mean temperature, the model specifies the heat flow between the thermal mass and the surrounding zone as a essential initial parameter.

The determination of the heat transfer resistance is sensitive: assuming that low flows occur in bottles (good heat transfer), but relatively high flows occur in stainless steel tanks (poor heat transfer), heat transfer coefficients can be determined. In outgoing pallets, the difficulty also lies in determining the heat transfer resistance due to the interaction of foiling, cardboard, glass bottles and intermediate air space. From an own simulation model (cardboard and foil as envelope and bottles as thermal masses in the envelope volume) an equivalent U-value could be determined. The thermal conductivity of cardboard was chosen according to Frick [12]. All selected input parameters are summarized in Table 1.

Table 1. Summary of the input parameters for describing the thermal masses

	specific heat [kJ/K]	surface area [m²]	U-value [W/m².K]
lattice cages (each cage incl. bottles)	1.530	27,0	7,0
production tank insulated (500 hl)	209.000	83,5	0,37
uninsulated (1000 hl)	418.000	118,9	3,30
palette outgoing goods (each palette incl. bottles)	1.350	8,0	3,0

2.3 Heat inputs

In the storage areas investigated, considerable heat input occurs during the production process starting with the delivery of the unfermented grape must and ending with the removal of the sparkling wine cages from the sparkling wine storage to disgorging. During this period, numerous production-related temperature changes and thus heat inputs take place in the stored goods. It had to be considered that production starts with delivery in different batches. Therefore, in addition to the temporal effect of the thermal masses, the heat development in the different batches had to be simulated separately.

Heat generation in the batches was divided into four phases: (1) the incoming goods phase with a certain initial temperature upon entry into the respective zone; (2) the production phase in which the stored goods are subjected to temperature changes as a result of the active production process and heat inputs therefrom; (3) the storage phase in which the temperature of the stored goods is continuously adapted to the air temperature in the respective zone; (4) the regeneration phase after removal of the batch from the zone in which the temperature of the stored goods is again adapted to the initial temperature upon receipt of the goods. The heat input into the thermal mass is accordingly defined by the initial temperature in the incoming goods phase and by the active production-related temperature changes during the production phase. The time for cooling down during the storage phase were compared with empirical values, to verify the assumptions about U-values of tanks and bottles.

3 Results

The central question of this investigation was whether the operation of individual areas of large-scale sparkling wine production without active heating and cooling can be guaranteed exclusively by passive conditioning via the soil. For this purpose, the floors and walls in contact with the ground should be constructed completely without insulation. The basic answer to the question is shown in figures 2 and 3. They show annual temperature development (beginning with the wine storage in September) for air temperature (t_{air}), selected batches of the stock (t_{bottle} or t_{tank}) and the soil directly adjacent to the bottom plate (t_{earth}) in the zones “wine hall” (Fig. 2) and “sparkling wine storage” (Fig. 3).

In the zone wine hall, after storage of the grape must at a temperature of around 20 °C in the incoming goods phase at the end of August (batch 1), the grape must stored in tanks is cooled down and the room and soil temperatures rise at the same time. This is followed by alcoholic fermentation in the production phase, followed by cooling to 6 °C for about two weeks at batch 1. After the storage phase, batch 1 is filled into bottles at the beginning of January and thus leaves the investigated zone. The thermal masses regenerate to the initial temperature during the regeneration phase until they are stored again. In this phase, only about one third of the capacity in the wine hall is occupied with stored old wine (batch 2), which is transferred from the sparkling wine hall in December at 17 °C and stored for a longer period.

The air temperature of the zone is decisively determined by the temperature of the stored goods. It is slightly below the temperature of the thermal mass during the winter months and slightly above it during the summer months. Minor fluctuations are caused by ventilation, solar radiation and other heat inputs (agitators). During the incoming goods phase, the air temperature briefly exceeds the specified limit value of 14 °C, but this is attributable to the production process and must therefore be viewed uncritically. In the further course of the year, the standard value of 12 °C is permanently undercut. The minimum temperatures are around 9 °C. The phase shift caused by the thermal masses of the soil and the stored goods can be clearly seen: While the minimum outside air temperatures occur in January, the lowest air temperatures of the zone and the stored goods do not follow until April.

Fig. 2. Annual course of selected temperature values for the zone „wine hall” (Ingenieurbüro Gratzl)

The findings gained in the zone wine hall can also be largely transferred to the sparkling wine storage in figure 3, but differ in one essential point: due to the low thermal mass and large surface area of the bottles stored in the lattice cages, the temperature of the stored product very quickly follows the air temperature. If the storage of new lattice cages with an initial temperature of 17 °C from the fermentation storage stops during Christmas holidays

or at the end of the incoming goods period in July as a significant heat input, a faster drop (winter) or a slower rise (summer) of the air temperature in the zone can be seen quite suddenly. Accordingly, the effect of the thermal masses of the stored goods in the sparkling wine storage unfolds much more quickly than that of the soil. The phase shift at the lowest temperatures at the beginning of March is also much less significant than in the wine hall with thermal masses of approximately the same size, but with a much lower surface-to-volume ratio of the tanks compared to the bottles in the lattice cages of the sparkling wine storage.

The upper limit of the target temperature of 12 °C is temporarily exceeded in late summer and autumn. The maximum temperature of 14 °C can be maintained throughout the year. In order to meet this requirement, however, the above-ground parts of the thermal building envelope must be of very high thermal quality: flat roof ($U = 0.12 \text{ W/m}^2\text{K}$) and exterior wall ($0.15 \text{ W/m}^2\text{K}$) must meet very high thermal requirements in order to enable passive ground cooling. With these requirements, the specifications for storage conditions can also be met in case of foreseeable climate change in the next thirty years. Without the foreseeable increase in the mean outdoor air temperature and, accordingly, the ground temperature, the requirements for the thermal building envelope could be reduced somewhat.

Fig. 3. Annual course of selected temperature values for the zone “sparkling wine storage” (source: Ingenieurbüro Gratzl)

In the sparkling wine hall with a specified room temperature of 17 °C (not to be confused with “sparkling wine STORAGE” with target temperature of 12 °C), the investigation showed that without insulation of the components in contact with the ground, the heat losses would significantly exceed the positive effect of passive cooling. Accordingly, the components of the sparkling wine hall that came into contact with the ground were equipped with sufficient thermal insulation. However, there is still a need for heating at the end of winter and cooling in late summer.

4 Discussion

The use of passive ground cooling for the conditioning of storage and production areas is a reasonable supplement to other passive cooling measures in this context. The presented approach of being able to completely avoid active heating and cooling in the sparkling wine storage and in the wine hall of a modern sparkling wine production through uninsulated ground-coupled components was confirmed by this investigation. Through the interaction of thermal storage of the stored goods and the adjacent soil, the heat input from the

production processes can be compensated and the storage conditions can be sufficiently fulfilled.

The present study is a single case study. Accordingly, the results derived therefrom are primarily limited to the prevailing boundary conditions for use, climate data, soil conditions and building geometry. However, a subsequent investigation with a similar task, but with a different geometry and at a different location in Austria, was able to confirm the results obtained. Accordingly, individual basic statements should also be able to be transferred to other projects. In any case, however, it is necessary to adhere to various boundary conditions:

- The limitation to passive cooling is only possible if the required room temperatures allow a fluctuation range of about 8 to 14 °C. If the limits are set closer, it must be considered that the heat input must be limited.
- High requirements must be placed on the thermal quality of the building envelope. Without sufficient thermal insulation of the exterior walls and the flat roof, the heat input during the summer months cannot be reduced to such an extent that the cooling effect of the ground has sufficient effect at the low target temperatures.
- The level of the base plate must be at least three metres below the adjacent ground level. Otherwise, the effect of passive ground cooling is not sufficient to achieve satisfactory results. Walls in contact with the ground must therefore be insulated to a depth of 2.0 m, as otherwise unfavourable heat input would occur at certain times in this area.
- The effectiveness of large thermal capacities of stored goods is largely dependent on the one hand on their surface-volume ratio and on the other hand on the heat transfer resistance of the shell elements. The larger the surface area in relation to the heat thermal capacity, the faster the thermal mass is heated or cooled. The time over which the heat storage becomes active differs accordingly: While large-volume production tanks adapt to room temperatures over a period of several weeks, individual bottles (even with a large number) absorb temperature changes within a few hours.

In particular, the high influence of the heat transfer resistance of the shell elements of stored goods on their effectiveness as heat storage leads to the fact that this has to be considered in detail. Since these are mostly materials with low thermal resistance, the heat transfer resistances - and especially those to the storage medium - are of great importance for the overall effectiveness. The flow conditions in the stored goods also influence the heat transfer and thus the overall effectiveness. This aspect of the investigation was only marginally considered in the present study.

The use of passive ground cooling as the exclusive cooling measure is limited to pure storage areas without significant heat input and to production areas with only minimal heat input of less than 2-3 W/m² on an annual average, if the maximum temperatures must not exceed 12 °C. As an additional passive cooling measure - for example also to reduce the active cooling requirement - it is, however, useful if it does not contradict any comfort or hygiene requirements.

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