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Experimental analysis of thermal interaction between wine cellar and underground

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ABSTRACT

Premises for wine storage and ageing call for a specific indoor climate, which can require high energy consumptions. Underground buildings have the potential to reduce energy demand in comparison to conventional aboveground buildings, by exploiting soil temperatures and ground cover. But the building–underground interaction is site-dependent, therefore an accurate design must take into account every aspect of the thermal interface between them. The objective of the study is to identify the time variations of temperature distributions related to ground layers involved in the interaction with underground buildings in the wine sector. The experimental monitoring system for surface ground temperature and shallow temperature beside and below an underground cellar is described. Based on data acquired, a numerical interpretative and predictive model for temperature behaviour in surface and shallow layers was developed. The model was calibrated through specific parameters able to account for the interaction with buildings. The equations developed proved suitable to reproduce the phenomena surveyed. Therefore, they allow to correctly design the interface between underground buildings and the terrain, on the basis of temperature data which can be surveyed in the soil at different depths, or within already existing underground artefacts.

1. Introduction

In wine production processes, stages of conservation and aging are fundamental for wine quality and have therefore been the subject of several studies aimed at identifying the optimal temperature and humidity conditions [1,2]. The large literature on the subject suggests that in most cases relative humidity of wine aging cellars should be not less than 70%, and temperature between 9 °C and 20 °C, with a maximum range of temperature oscillation around 6 °C. In fact these conditions allow an adequate development of wine, containing within acceptable limits the weight losses due to evaporation and leakages from the barrels [3]. At the same time many authors proposed ways to design wineries in order to achieve appropriate environmental conditions for wine (proper orientation, solar protection, controlled ventilation) [4]. They highlighted the advantages of underground building to ensure thermal stability [5,6], avoiding excessive temperature fluctuations [7], to contain contractions and expansions of the liquid [8].

Premises for wine storage and ageing are definitely among the built spaces, which need a specific climate. In past ages, one of the solutions for the preservation of food products, particularly wine, consisted in placing products in basements [9,10]. Thanks to the well-known thermal characteristics of ground, they favour the maintenance of thermo-hygrometric conditions suitable for preservation [11]. From the second half of the last century, it was preferred to delegate temperature and humidity control, necessary for aging wine, to air-conditioning systems, given the high construction cost of underground buildings and the relatively low cost of electricity. Such systems provide predetermined temperature and humidity with a high degree of control and precision against an energy consumption which is in close dependence with the surrounding environmental conditions (including the site, orientation of the building, weather conditions, architectural and plant solutions adopted, etc.) [12]. Design choices have therefore been largely oriented towards predominantly single-storey aboveground buildings [13,14].

Direct surveys and interviews carried out on a representative wine production area [15] showed that currently the energy requirement related to the product conservation accounts for approximately 50% of the total demand for the production of still

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Nomenclature

A	external temperature wave amplitude (°C)
A_{tot}	underground temperature wave amplitude (°C)
h	"vegetation and shading influence" design parameter
K	"air influence in the cellar" design parameter (°C)
L	heat exchange distance (m)
P	heat flux intensity (W)
r	upper limit of the underground cellar (m)
s	lower limit of the underground cellar (m)
S	heat exchange area (m^2)
t	time (d)
t_0	time of minimum external temperature (d)
$t'_{0,\,max}$	"upper wall influence" design parameter (d)
$t'_{0,\,min}$	"Lower wall influence" design parameter (d)
$\bar{T}$	daily average value of underground temperature (°C)
T_m	annual average value of external temperature (°C)
x	depth (m)
α	equivalent underground thermal diffusivity (m^2/d)
ϕ	wave shift (°)
η	"aboveground building influence" design parameter (–)
λ	thermal conductivity (W/(m K))
τ	wave time shift (d)

wine. In case of end products such as the classic method sparkling wine or champagne, where the entire production is aged in the bottle for long periods – up to five years – the consumption for the air conditioning have a larger impact. Surveys carried out on a significant Italian study case underlined that energy consumption during the 10 months of the year excluding harvest period is on average 57% of the total, and it is due almost entirely to air conditioning of underground rooms for aging in bottle. 43% of consumption is thus recorded during the months of September and October; this consumption is mainly attributable to winemaking operations, but also in large part to the air conditioning of the premises. Therefore, the energy demand for air conditioning of the room for wine storage and second fermentation in bottle, is assessed between 65 and 70% of the total [16].

In recent years, the gradual increase in energy costs, the regulatory guidance aimed at energy saving [17] and the increasing environmental awareness of the public, are pushing research and market towards the assessment of building products also from the energy point of view [18]. Building solutions characterized by low energy consumption have therefore been preferred, with a consequent new interest for the burying of wine storage buildings. In fact underground buildings have the potential to reduce energy demand in comparison to conventional aboveground buildings, by exploiting the beneficial soil temperatures and ground cover as insulation [19,20]. In fact, underground wine cellars have a relatively low energy request for the ground potential of temperature peaks damping, thermal wave phase shifting and temperature variation breaking down, besides favouring the reach of adequate moisture levels for wine storage and aging [21]. With this purpose, the design of underground wine cellars calls for the knowledge of ground temperature distributions at various depths of surface and shallow underground layers. Moreover, the temperature gradient in the soil around the cellar has to be defined, in order to correctly model the ground–building interactions. This implies a proper investigation of temperature profiles at various distances beside cellar walls and below its floor.

The analysis of underground temperature distributions in surface and shallow layers has been the subject of various studies, which have been considered for the setup of the research. In this regard Mihalakakou et al. [22] developed a transient, numerical model for the prediction of the ground temperature at various depths below buildings, by calculating the heat flow to the ground from a building, accounting for the three-dimensionality of the thermal process, the temporal variability of outdoor temperature, the building foundation geometry, and thermal insulation. Jacovides et al. [23] studied soil temperature oscillations with experimental trials up to depth of 1.2 m, founding that at any time they can be estimated on the basis of harmonics computed by Fourier techniques. In particular, the first three harmonics together provide good agreement with observed temperatures at various depths. Moreover Mihalakakou [24] estimated soil surface temperature profile in Athens using an analytic deterministic model based on the transient heat conduction differential equation with the energy balance equation at the ground surface as boundary condition, and a neural network model based on back propagation algorithm for the estimation of hourly values of soil surface temperature. The analytic model gave slightly better estimations than the data-driven model for the warm period of the year, while the analytic model gave better estimations for the cold period as it could account for weather phenomena. van Manen et al. [25] developed a model to estimate separately the temperature distribution in underground with reference to the surface behaviour (influenced by daily variation), the shallow one (influenced by seasonal variation), and the deep one above the level of geothermal gradient influence. By taking into account these three different behaviours, thermal properties of the three zones can be computed.

This paper develops the second part of the research described in [26]. The objective of the study is to identify the time variations of temperature distributions related to ground layers involved in interaction with underground buildings in the wine sector. In particular, [26] presented the monitoring campaign of underground temperatures, provided an analytical model for temperature behaviour in shallow layers, and proposed a procedure based on non-linear regression for the assessment of soil thermal diffusivity. In this paper, the experimental monitoring system for surface ground temperature and shallow temperature beside and below an underground cellar is described. Based on the data acquired, the research aims at the development of an analytical interpretative and predictive model for temperature behaviour in surface and shallow layers. Moreover, the study aims at calibrating the model through the identification of specific parameters able to account for the interaction with underground and aboveground buildings.

2. Materials and methods

2.1. The case study

The case study considered consists in a wine farm in the Emilia-Romagna Region (Italy), whose representativeness has been discussed in [26]. The farmstead includes a building with two aboveground storeys and an underground cellar for wine aging. The latter has inner plan dimensions of 5.60 m × 9.80 m, with the floor located 2.90 m below the ground, and inner height of 2.50 m. This cellar has only one window located on the north-eastern wall and a door on the north-western wall, and can contain up to 45 barrels. The walls are made of 25 cm thick brick masonry, the floor is paved with baked clay bricks on a 20 cm concrete slab, the ceiling is a 30 cm thick hollow concrete slab. The cellar is naturally ventilated with free running indoor air temperatures, while the room above is a residential space with heating system.