Microventilation system improves the ageing conditions in existent wine cellars

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Abstract

Background and Aims: The importance of indoor environmental conditions in a cellar is well known and continuously investigated. The process of wine ageing consists of several steps, during which temperature (T) and relative humidity (RH) play a fundamental role as the quality of the final product is strongly related to stable and suitable environmental conditions. Critical factors, such as mould growth or wine evaporation, have emerged when ventilation has proved to be insufficient or poorly designed. The limitation of stagnant areas and the homogeneity inT and RH provide for proper wine conservation; however, unwanted local conditions can occur in the zones with insufficient air exchange.
Methods and Results: Considering these aspects, a controlled microventilation and monitoring system was installed in a case study cellar, and T and RH were monitored for 1 year. The data have been analysed to investigate criticalities of the environmental conditions. The ventilation was activated in specific critical conditions to increase the homogeneity of the T and RH in the critical zones. The results show that the microventilation system improves the homogeneity of both T and RH without affecting the average values.
Conclusions: The study demonstrated the efficacy of the system and indicated possible modifications to improve system performance.
Significance of the Study: The system proved to be a useful tool for both improving the environmental conditions and providing useful information to the winemakers about the ageing conditions.

Keywords: *control system, data analysis, indoor air monitoring, microventilation system, wine cellar*

Introduction

For some time, research has investigated and identified ideal room conditions for wine ageing in wooden barrels (Arredondo-Ruiz et al. 2020). The temperature values for wine conservation cover the range from 9 to 20°C (Troost 1953), and Vogt (1971) has indicated that temperature variation should be maintained lower than 6°C. Togores (2003) has suggested that the optimal RH should be higher than 70% in order to avoid excessive evaporative wine losses because they are strictly dependent. Negrè and Françot (1965) have shown that a temperature higher than 18°C and an RH lower than 45% can significantly affect wine conservation, causing losses of up to 10% in volume per year. Considering these aspects, Ruiz De Adana et al. (2005) have developed a mathematical model that correlates wine losses to the indoor environmental conditions, thus quantifying the effect of air velocity, temperature and RH on wine evaporation from wooden barrels. Despite its importance, currently, the literature does not report optimal or limit values for indoor air velocity (Barbaresi et al. 2015a,b).

Another critical aspect for wine conservation is the absence of mould and other fungi growing on the surfaces of wood barrels, which can be facilitated by high RH inside the cellar (Pasanen 2001). Therefore, usually, mould and fungal growth is strictly monitored in cellars as it can contaminate and affect wine sensory properties (Simeray et al. 2001). Related to this issue, as well as for the residential sector (Asphaug et al. 2020, Kwan et al. 2020), Ocón et al. (2011) have observed that the efficiency of natural ventilation is an important factor to reduce mould presence in the air, consequently decreasing its possible growth on the barrels (Fortenberry et al. 2019). Despite this observation, there are few studies on the effect of natural ventilation in wine cellars (Martín Ocaña and Cañas Guerrero 2006, Cañas and Mazarrón 2009). For example, Geyrhofer et al. (2011) indicates normal values, ensured by conventional natural ventilation, of air velocity in the range of 0.3–0.4 m/s. Ventilation efficiency, however, could be insufficient to maintain constant and optimal conditions inside the cellar because it is strictly dependent on the external climatic conditions (Santolini et al. 2019, Zhao and Chen 2019). Ventilation in a wine cellar should be able to ensure homogeneous conditions of temperature and RH, avoiding areas of stagnant air in order to limit wine losses and to avoid mould growth.

Based on these considerations, we have selected a wine cellar as a case study where the indoor climatic conditions have been monitored for over 1 year. The temperature and RH data have been collected in the cellar, and the preliminary analysis of Barbaresi et al. (2014) has allowed the zones with the highest risk of air stagnation to be defined. A preliminary analysis of the data has identified the critical areas, located behind the wood barrels, close to the perimeter wall, confirming a previous computational fluid dynamic (CFD) analysis (De Rosis et al. 2014). This situation can be considered common in existent wine cellars and can be approached as a localised problem of proper ventilation

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efficiency (Kabanshi and Sandberg 2019). The improvement of specific localised conditions has been investigated with the implementation of an additional ventilation system, as already experienced in residential (Andersson et al. 2018) and in other agro-industrial structures, such as greenhouses and livestock farms (Yoshino et al. 2003, Mondaca and Choi 2016, Wang et al. 2018).

In this study, a smart localised ventilation system, previously designed by Santolini et al. (2019), has been optimised, implemented and tested in the case study cellar. The system has been activated, under particular room conditions, from a specifically programmed control system. The activity of the ventilation system has been monitored for over 1 year, and in order to evaluate its main effects, the results obtained have been compared to the actual conditions in the wine cellar. The purposes of the study are: (i) identification of the most critical conditions affecting the critical zones (based on the monitored data); (ii) ventilation system assessment in comparison with current conditions; and (iii) analysis of the major conditions for the activation of the system.

Materials and methods

Microventilation system

The homogeneity of the indoor conditions plays a key role in the conservation and ageing of wine in cellars. The air velocity magnitude (v) inside the room, and in particular around the barrels, should ensure adequate temperature (T) and relative humidity (RH) levels to avoid, or minimise, mould growth and wine losses from evaporation. Based on this, in the present study, the implementation of an additional ventilation system has been considered in order to properly move the air behind the barrels to avoid air stagnation and to obtain, locally, a more homogeneous distribution of T and RH. Even though the scientific literature reviewed does not report any upper limit, according to the wine producers' experience, inside a wine cellar, the air flow should have a velocity lower than v_{max} = 1 m/s, which has been selected in the present study as the upper limit in the design of the ventilation system. The literature indicates that common values of v, in cellars for wine conservation, range from 0.3 to 0.4 m/s (Vogt 1971, Geyrhofer et al. 2011). This range has been selected for the configuration of the ventilation system as the system must ensure this target range of air velocity close to the barrels. For these reasons, the microventilation system has been designed to maintain a constant and uniform air flow in the area of the barrels. The system has been constructed using as reference the ventilation systems made of fans and pipes usually implemented in the agricultural sector for the localised ventilation systems in livestock barns and greenhouses. The system is composed of three main parts: (i) a monitoring system, that is, T and RH sensors located on the barrels and in the centre of the room; (ii) the ventilation pipes, powered with 220 V personal computer fans; and (iii) a control board used to monitor, control, record and show the data.

Specifically, the polyvinylchloride ventilation pipes have a diameter of 125 mm and contain holes of a diameter of 5 mm drilled at 6.25-cm spacing (Santolini et al. 2019). One of the pipes is shown in Figure 1 during the preliminary laboratory tests.

Santolini et al. (2019) characterised several set-ups of the ventilation system according to the number of holes, and their spacing and diameter, and evaluated ventilation performance and efficiency at a distance equal to 40 cm (considered representative of the usual distance between the wall and barrels in existing cellars). Of all the set-ups evaluated, the configuration chosen in this work ensured a value of v of about 0.4 m/s measured close to the barrels. The system has been implemented in the wine cellar with the main aim of monitoring and measuring its effects in the barrel area. The data collected will allow the assessment of the effectiveness of the system in improving the homogeneity of climatic condition.

Figure 1. Microventilation system created for the cellar.

Description of the case study

The experimental campaign was conducted at a wine farm in the countryside of the Bologna Province (Italy). The farm currently produces 2500–3000 hL of wine per year, and about 2–5% of this wine is aged in a cellar in wooden barrels. The cellar is an underground room (Figure 2) 9.0 m long, 5.0 m wide and 2.6 m high. The environmental conditions, that is, T and RH, have been monitored since 2012 (Benni et al. 2013, Barbaresi et al. 2015b), allowing several studies on thermal (Tinti et al. 2015, 2017) and CFD analyses(De Rosis et al. 2014).

In particular, De Rosis et al. (2014) and Barbaresi et al. (2015b) highlighted some critical situations for the wine ageing phase as explained in the following sections. Previous studies on the case study cellar had shown that the

Figure 2. The monitored wall during the experimental tests.

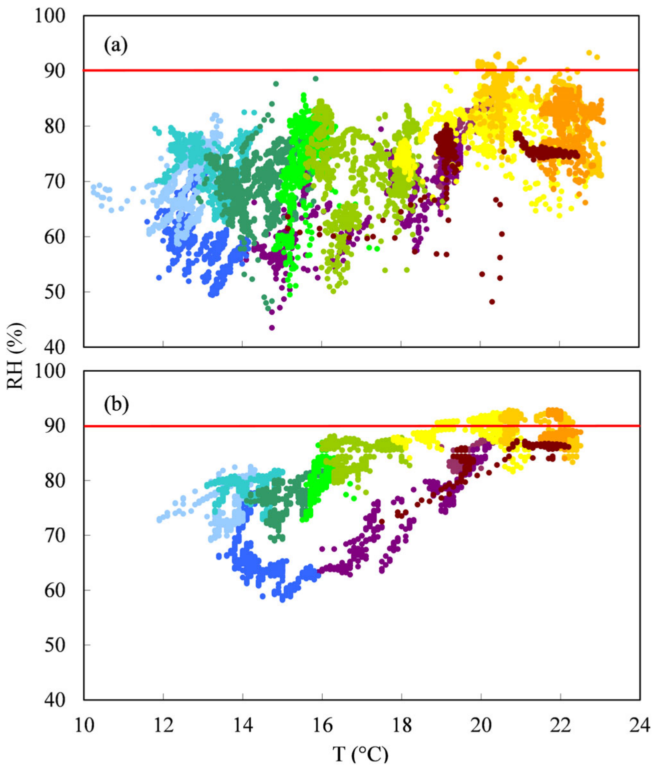

Figure 3. Temperature (T) and relative humidity (RH) hourly data recorded: (a) in the centre of the cellar (by two sensors) and (b) close to the perimeter wall (one sensor), behind the barrels according to the methodology explained in Barbaresi et al. (2015b). October 2013 (●), November 2013 (●), December 2013 (●), January 2014 (●), February 2014 (●), March 2014 (●), April 2014 (●), May 2014 (●), June 2014 (●), July 2014 (●), August 2014 (●) and September 2014 (●).

zone between barrels and underground walls (Barbaresi 2014, De Rosis et al. 2014, Barbaresi et al. 2015a,b), a space 30–40 cm wide, exhibited the lowest air velocity values and therefore the highest risk of air stagnation. In these areas, natural ventilation guaranteed v far below 0.2 m/s, considered the lower limit for v in cellar, provided by the natural ventilation (Geyrhofer et al. 2011). This outcome has been confirmed by previous experimental campaigns conducted in the case study cellar. Indoor T and RH have been monitored for approximately 2 years, between 2012 and 2015, by means of stand-alone thermo-hygrometer data loggers placed in the centre of the room and in the perimeter wall facing the barrels, that is, 20–30 cm away from the barrels (Barbaresi et al. 2015b). The collected hourly data have returned a precise picture of temperature and RH related to the most critical situations in terms of time and position in the cellar. Hence, from Figure 3, it is evident that space between barrels and wall is characterised by RH that is considerably higher than ideal during the summer period. On one side, only 0.6% of the values of the RH measured in the centre of the room exceeds an RH value of 90%. On the other side, in the space close to the wall, the RH has been recorded for 7.9% of the time over 90%. Starting from this preliminary analysis, the experimental layout and set-up used in this work have been carefully defined with the objective to further investigate the problem and to test the effectiveness of a possible solution.

Experimental test

The wall shown in Figure 2 has been chosen for the experimental test. In particular, the steel structure supporting 14 barrels is arranged in three horizontal rows that hold, respectively, 5, 4 and 5 barrels. The area between the wall and barrels has been divided with a cardboard panel in two different portions, defined as non-ventilated wall (nVW) and ventilated wall (VW). A three-dimensional view of the case study cellar is given in Figure 4.

The non-ventilated portion is on the left side of the wall, whereas the ventilated portion is on the right. In Figure 4, the barrels close to the monitored wall are red coloured if corresponding to the VW portion, whereas they are purple coloured if they correspond to the nVW portion. The light blue barrels were not monitored and not the object of the study. The two horizontal pipes of the ventilation system, coloured in green in the figure, are obviously installed only on the right side of the monitored wall. The two pipes have been located horizontally between the first and the second row and between the second and the third row as shown in Figure 5. This experimental configuration has been used to compare the environmental conditions between:

- the area of the cellar without the microventilation system (i.e. current situation) and the area equipped with the microventilation system (i.e. improved situation);
- the fans-on and fans-off configurations in the area equipped with microventilation system.

The right extremity of each pipe has been provided with a fan, whereas the left extremity has been sealed with a plastic cap. Each pipe has air flow oriented 45° downwards from the horizontal row. Each barrel has been equipped with a sensor positioned at the centre of the barrel side facing the wall as, according to De Rosis et al. (2014), that is the most critical side. The two barrels that belong to both the zones have been provided with two sensors, one for each wall portion (i.e. ventilated and non-ventilated). The identification code of the sensors has been reported in Figure 5. Each sensor, for the monitoring duration, recorded T and RH in correspondence of the barrel.

An additional sensor (#17) was placed at the centre of the cellar in order to represent the typical indoor environmental conditions as demonstrated in Barbaresi et al. (2015b).

Software has been programmed for the management and the activation of the microventilation system if one of the critical conditions occurred. Considering that the literature lacks precise indications to set the system, the limit values, for the identification of the critical environmental conditions, have also been established in agreement with the owner requirements. The main aims of the conditions that will be introduced in the following are:

- to avoid mould growth, and therefore, local and global RG should not reach an excessively high value;
- to avoid different ageing conditions among barrels, and therefore, homogeneous T and RH should be eased.

The combination of literature values (Vogt 1971, Marescalchi 1975) and owner experience led to the definition of the limit values reported in Table 1.

Four conditions activating the microventilation system were then defined as follows:

- Condition 1 (C_1): At least one sensor in the barrels measures an RH value ($H_{b,i}$) higher than the maximum allowed value ($H_{b,\max}$), that is, $\exists H_{b,i} \geq H_{b,\max}$;
- Condition 2 (C_2): The average RH value (H_a) of the barrel group in the ventilated wall portion (i.e. barrels with code

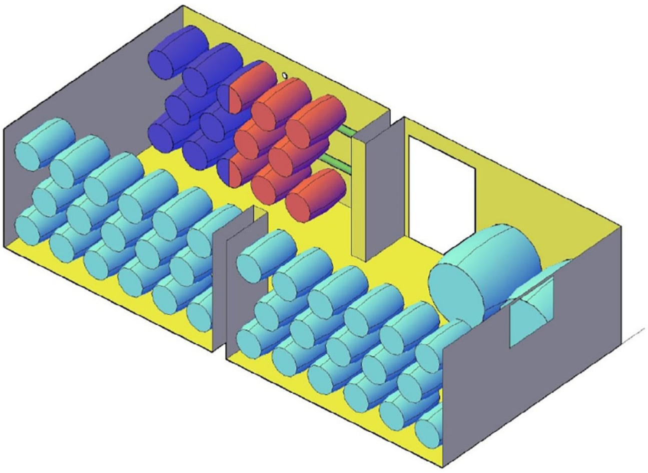

Figure 4. Three-dimensional view of the case study cellar. The pipes are depicted in green, and the barrels close to the monitored wall are red coloured if corresponding to the ventilated wall (VW) portion and are purple coloured if they correspond to the non-ventilated wall (nVW) portion.

#1–#8) exceeds the maximum allowed average RH for a barrel group ($H_{a,\max}$), that is, $H_a \geq H_{a,\max}$;
- Condition 3 (C_3): The absolute value of the difference between the average RH of the barrel group (H_a) in the ventilated wall portion and the RH of the room (H_r) exceeds the maximum allowed RH difference (H_d), that is, $|H_a - H_r| \geq H_d$; and
- Condition 4 (C_4): The absolute value of the difference between the average T of the barrel group (T_a) in the ventilated wall portion and the Tof the room (T_r) exceeds the maximum allowed T difference (T_d), that is, $|T_a - T_r| \geq T_d$.

The control system has been programmed to activate both the fans if at least one of the four conditions is attained and to keep the fans off as long as the four conditions have values lower than the limits. The monitoring rate has been set to every 10 s, while the fan activation check was performed every minute. The test started in July 2016 and ended in June 2017, covering an entire year of monitoring. The test was suspended on a few occasions for farm needs, such as cleaning, barrel check and filling and treatments. The system recorded over 500 000 measurements for each sensor.

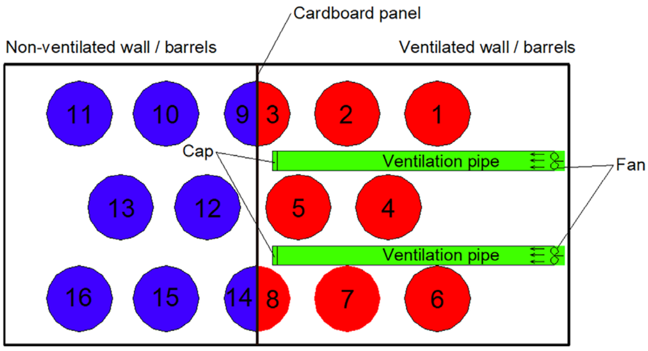

Figure 5. Scheme showing the two portions of the cellar monitored wall and the sensor codes of the barrels. The pipes of the microventilation system are depicted in green, and the monitored barrels in the ventilated wall portion are red coloured with codes #1–#8, and the monitored ones in the non-ventilated wall portion are purple coloured with codes #9–#16.

Table 1. Limit values assumed for the definition of the conditions activating the microventilation system.

Symbol	Description	Limit value
$H_{b,\max}$	Maximum RH allowed for a barrel	90%
$H_{a,\max}$	Maximum average RH allowed for the barrel group	87%
H_d	Maximum RH difference allowed between H_a and H_r	15%
T_d	Maximum temperature difference allowed between T_a *and* T_r	3°*C*

Control system and sensor probes

The microventilation system has been controlled and managed by an Arduino-based system, which has these functions:

- monitoring T and RH in the zone between perimeter wall and barrels;
- identifying when environmental conditions become critical (i.e. at least one of the critical conditions C_1–C_4 is attained);
- keeping the fans off in normal environmental conditions;
- switching on the fans when conditions in the cellar room become critical;
- displaying, in real time, the monitored data; and
- recording all the data.

The flow chart of the implemented code is depicted in Figure 6. The system has been composed of an Arduino board equipped with the following additional parts:

- 17 thermo-hygrometers probes (DHT22), one for each barrel (two for the barrels located between the two portions) and one in the centre of the room recording cellar environmental conditions;
- 14 × 20 LCD display;
- one secure digital (SD) card board; and
- two relays to control the activation of the fans.

The boards, the display, the relays, the charger and the sensor connections have been located, for protection, in a commercial IP65 (IP Code, International Protection Marking, IEC standard 60 529) enclosure case (Fitting SRL, Bologna, Italy). For precise monitoring, the sensors DHT22 (Table 2) have undergone a calibration procedure using a CH 150 CLIMATEST climate chamber (Argo Lab, Carpi, Italy). In particular, the chamber has allowed the testing of the sensors under three different conditions, coupling T and RH. This procedure has allowed not only the testing of the reliability of the sensors but also the preparation of the calibration curve for each sensor by interpolating the measurement data.

Data analysis

The data collected have been analysed by two main approaches. The first approach consists of investigating the problems related to the non-ventilated area based on the guidelines imposed by the winery manager. The second approach aims to compare the different conditions between the VW and nVW portions.

First approach. The analysis has been conducted on the data collected on the nVW portion, which is representative of the

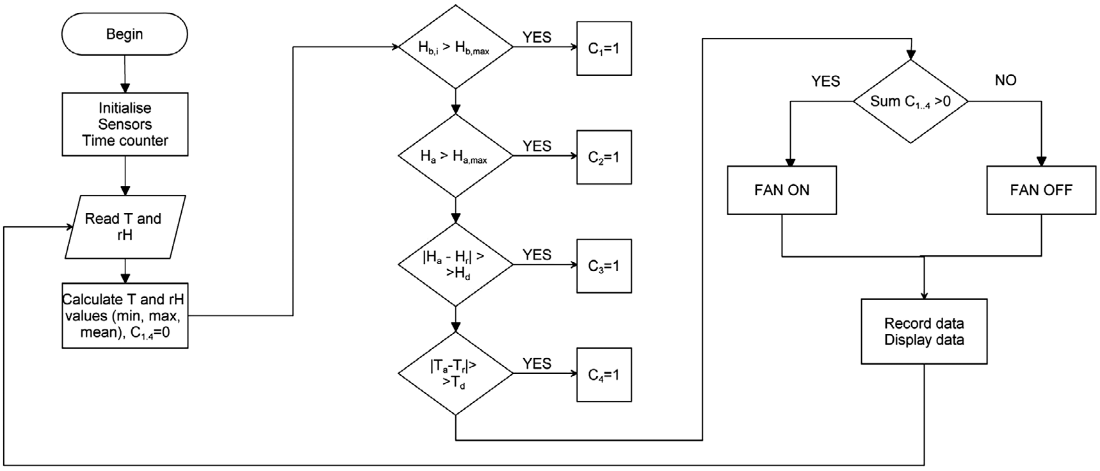

Figure 6. Flow chart of the code implemented in the Arduino board.

current conditions and provides information on the barrels in a naturally ventilated cellar. In this way, it was possible to identify the problems affecting the area, such as the spatial positioning of the barrels, and record the time histories of T and RH if only natural ventilation is present. The analysis has been conducted based on the limits defined in the section Experimental test in order to represent the reference for the test on the VW portion.

Second approach. This analysis has been focused on investigating and assessing the effectiveness of the ventilation system. The benefit of the system has been evaluated based on its capability to reduce the fans-on conditions and to improve the homogeneity of T and RH. The environmental conditions are better the lower the uniformity index. Homogeneity has been estimated using the SD of T and RH measurements for the barrels at different times.

Precisely, given relative SD (RSD) = σ/μ, the uniformity index (UI) has been defined as the average RSD considering the entire dataset of measurements available (Equation 1):

$$\mathrm{UI} = \sum_{k=1}^{N} \mathrm{RSD}_k / N \tag{1}$$

where UI is the uniformity index, RSD_k is the RSD value for the kth record and N is the total number of records. In the definition of RSD, the values of μ (mean) and σ (SD) are obtained starting from the values of T and RH recorded by the sensors on the barrels in the same group (i.e. ventilated with barrel codes #1–#8 and non-ventilated with barrel codes #9–#16).

Results and discussion

After a preliminary period of testing, used for a proper calibration, the recording time step was assumed equal to 1 min, which was suitable to capture the slow T and RH variation in the cellar. The total number of raw measurements was over 500 000 records for both T and RH and for each sensor. The resulting final data, however, had some missing records because of working operations in the barrel area or the cleaning procedures. The dataset was cleaned, and the resulting dataset has 227 156 measures (covering about the 43% of the entire year of monitoring) for 17 sensors (16 for the barrels and one for the cellar environmental conditions) and two values for each sensor (i.e. T and RH). The collected yearly data are distributed as follows: 65364 data in summer, 30 073 in autumn, 52 787 in winter and 78 932 in spring. Finally, the possible formation of mould and the deterioration of the barrels was observed, and no mould or deterioration was detected during the entire experimental campaign.

Temperature and RH distribution

The data collected in both the monitored wall portions have been compared, and the T and RH distributions, in the investigated period, have been obtained.

Figure 7 shows the probability distributions of the T values collected by all the sensors. Figure 7a shows that 37% of measurements in the nVW are within the 20–23°C range; distribution of all the other T values is lower than 8%, showing a high variability of T out of the above range. The higher distribution close to the higher Tdepends on the fact that the monitoring campaign was carried out in a discontinuous period, mainly during summer and spring, when the most critical conditions occur. Differently, Figure 7b shows three main peaks in VW around 9, 14 and 21°C that represent 69% (respectively, 26, 20 and 23%) of the total measurements. Considering that the two walls are under the same environmental conditions, this difference can be attributed to the ventilation system. To better investigate this aspect, the distribution of VW is represented according to the activation of the fans. Figure 7c exhibits the distribution of T values in VW when the fans are activated, and Figure 7d demonstrates the distribution when they are off. It is obvious that the three T peak values of Figure 7b are confirmed, but they appear in one of two conditions only: the 9 and 21°C peaks are visible in the fans-on configuration (Figure 7c) and 14°C peak in the fans-off (Figure 7d).

Table 2. Datasheet for the DHT22 sensors.

Model	DHT22
Operating range	RH: 0–100%; T: −40/+80°C
Accuracy	RH: 2% (Max ±5% RH); T: <±0.5°C
Resolution or sensitivity	RH: 0.1%; T: 0.1°C
Repeatability	RH: ±1%; T: ±0.2°C
Humidity hysteresis	RH: ±0.3%
Long-term stability	RH: ±0.5%/year
Sensing period	Average: 2 s

This is maybe because of the fans being activated mainly in extreme T seasons. A deeper analysis on collected data confirms that the fans are mainly operating when the T is out of the 13–16°C range. This is confirmed by comparing the Figure 7a,b, where the probabilities to be in this range are similar (20% for both VW and nVW), confirming that, when the fans are off, the wall portions have a similar T. Importantly, as it shows that, when the temperature is between 13 and 16°C (within the suitable range for wine ageing, particularly for white wines), the ventilation system is off, indicating that the RH is within a correct range.

Considering that 13–20°C is a suitable range for the ageing of all wines, however, the wine stored in the nVW is within the range for 36% of the time, whereas the wine in VW is in the range for 32% of the time. This confirms that the ventilation system does not improve the overall T of the wine under storage.

Figure 8 shows the probability distributions of the RH values collected by all the sensors. Figure 8a shows that 24% of measurements in nVW are over 90% of RH (considered the threshold for a single barrel as defined in Table 1), compared to the 18% of data related to the VW. Moreover, 53% (21% in nVW) of all data collected in the VW is between 85 and 90% (Figure 8b), which is considered a proper condition for wine ageing as both the wine evaporation and the mould formation risk are reduced.

Finally, this concentration of values (between 85 and 90%) can be seen as an improvement in terms of RH homogeneity (specific analyses are reported in the following sections). Median RH values are 88% for VW and 87% for nVW, showing that, for T, globally, no significant change in the RH was introduced by the ventilation system. This situation can be provoked by the distribution of the fans air that also involves the floor, where rising damp was detected.

Figure 8c,d report, respectively, the distribution of RH when the fans are activated and turned off. Even though differences do not appear remarkable, further analysis indicates that the RH exceeds 90% for the 18% of measurements in the fans-on condition versus 17% in the fans-off.

In fact, it is important to remember that fans are off when environmental conditions are suitable for wine ageing; therefore, it is not surprising to find slightly poorer RH conditions when fans are activated. This aspect will be better explained later.

Analysis of the data on ventilation system activation

To quantify the positive effects of the ventilation system, global data have been carefully analysed. The ventilation system was turned on for the 66.7% of the considered period, equal to 151 592 collected data (i.e. about 2526 h). The sensors behind each barrel made the analysis of the distribution of RH and T possible in both sections of the cellar (i.e. VW and nVW). The activation of the fans determines a change in the conditions of the room (air flows not normally present), and their activation is strictly dependent on specific environmental conditions. For these reasons, the correlation matrices between the different environmental conditions have been calculated for the two system configurations (i.e. 'on' or 'off'), and they are reported, respectively, in Tables 3 and 4. In the tables, the blue values refer to the correlation with $|R^2| > 0.75$; values are coloured in red when they show a correlation with $|R^2| < 0.75$ and the correspondent value in the other table has $|R^2| > 0.75$.

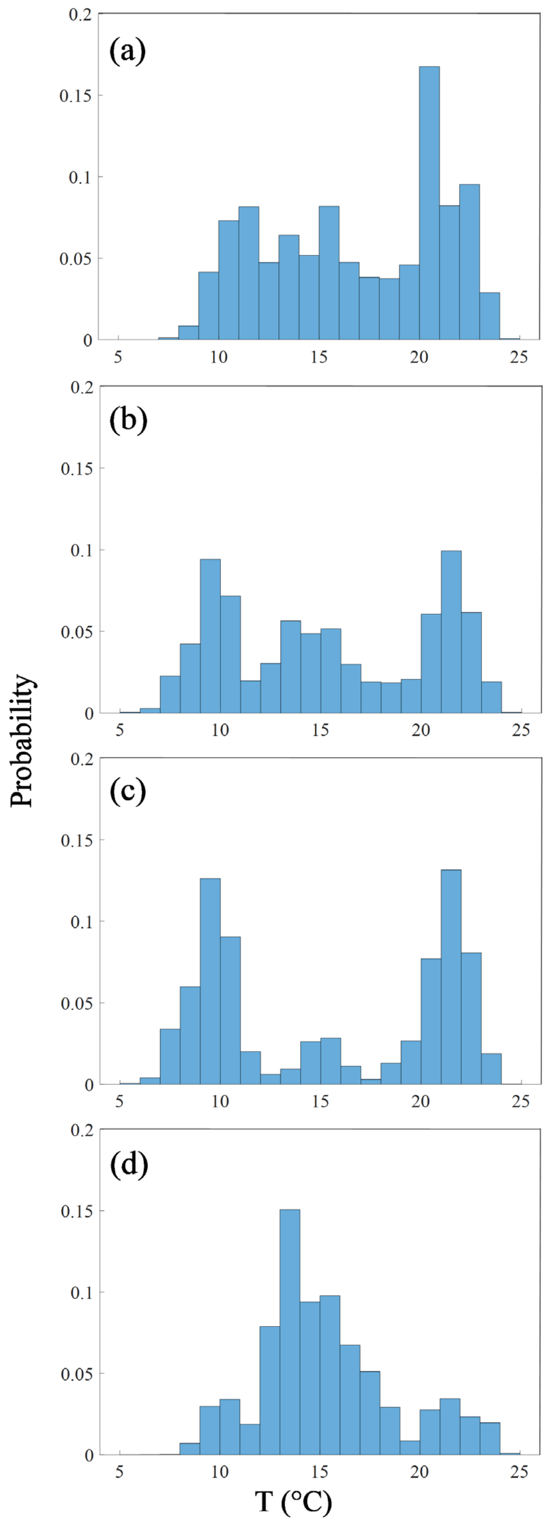

Figure 7. Probability distribution of the temperature T during the experimental campaign. (a) nVW case; (b) VW case; (c) VW case when fans are activated; (d) VW case when fans are off.

From the comparison of the two matrices, considering that all the correlations for which $|R^2| > 0.75$ are significant, it can be seen that:

- the T difference ($T_a - T_r$) is inversely related to its absolute value in both situations (row 7, column 4); this shows that the T of the room (T_r) is always greater than the average T of the barrels (T_a);

- maximum value of RH $H_{b,i}$ and average RH H_a (row 2, column 1) is highly correlated in the 'off' situation and is poorly correlated in the 'on' situation because, when turning on the ventilation system, the fans tend to homogenise the RH values, smoothing the peak values;
- maximum value of RH $H_{b,i}$ and cellar RH H_r (row 5, column 1) are correlated in both situations. A possible explanation can be the verified presence of 'RH source' in the cellar floor, such as water infiltration and rising damp. During particular periods of the year, the RH rises in local spots, affecting a few barrels and increasing the room RH;
- average RH H_a and absolute value of RH difference $|H_a\text{-}H_r|$ (row 6, column 2) are inversely correlated for fans 'on' and are poorly correlated for fans 'off'. This means the RH recorded in the ventilated portion is often lower than that recorded in the room (as a matter of fact, $|H_a - H_r|$ decreases when H_r increases only if the latter is higher than H_a); on the contrary, this correlation is not significant in the non-ventilated portion of the wall;
- average RH H_a and room RH H_r (row 5, column 2) are poorly correlated for fans 'on' and highly correlated for fans 'off'. With the fans 'off', the room RH tends to linearly depend on the average RH of the wall. In contrast, the fans redistribute the RH, involving air around barrels, walls and a portion of the floor. In the latter, the rising damp can affect the average value, creating an independency between average RH in the barrels H_a and that in the room H_r. This aspect needs further investigation;
- RH difference $H_a - H_r$ was inversely related to its absolute value (row 6, column 3) for the fans 'on', whereas they were poorly correlated for fans 'off'. This indicates that, with the fans running, the room RH is usually greater than the average wall RH; and
- in Table 3 (fans on), the room RH H_r was not correlated with any datum related to the barrels, indicating that the system helps to keep the variation in barrel and room RH independent.

The conditions under which activation of the system occurs are independent and can therefore occur separately and/or together.

The occurrences recorded for the four conditions C_1–C_4, described in the section Experimental test, can be verified and investigated. The number of occurrences for each condition and for their combinations are collected in Tables 5 and 6 for both the portions of the monitored wall. In the tables, the value '0' represents the state of non-exceeding of the condition, while the value '1' indicates the overcoming of the critical condition. The condition C_4 (i.e. $|T_a - T_r| > T_d$) never occurs in the VW nor in the nVW and, for brevity, has been omitted in the tables. Nevertheless, this shows that two faces of the barrels (one oriented towards the wall and the other towards the centre of the room) do not experience severe T differences, guaranteeing an important condition for wine ageing. One of the most important points that Table 5 makes is that the combination 0000 (corresponding to suitable conditions for wine ageing) occurs 69 395 times (31% of total measurements) in VW and 33 838 (15%) in nVW, showing the efficacy of the ventilation system.

As previously described, the four different conditions adopted for the turning on of the microventilation system can occur simultaneously. Based on this, the occurrence of each condition, of the total number of system activations, has been calculated, and some outcomes have been summarised in Table 7.

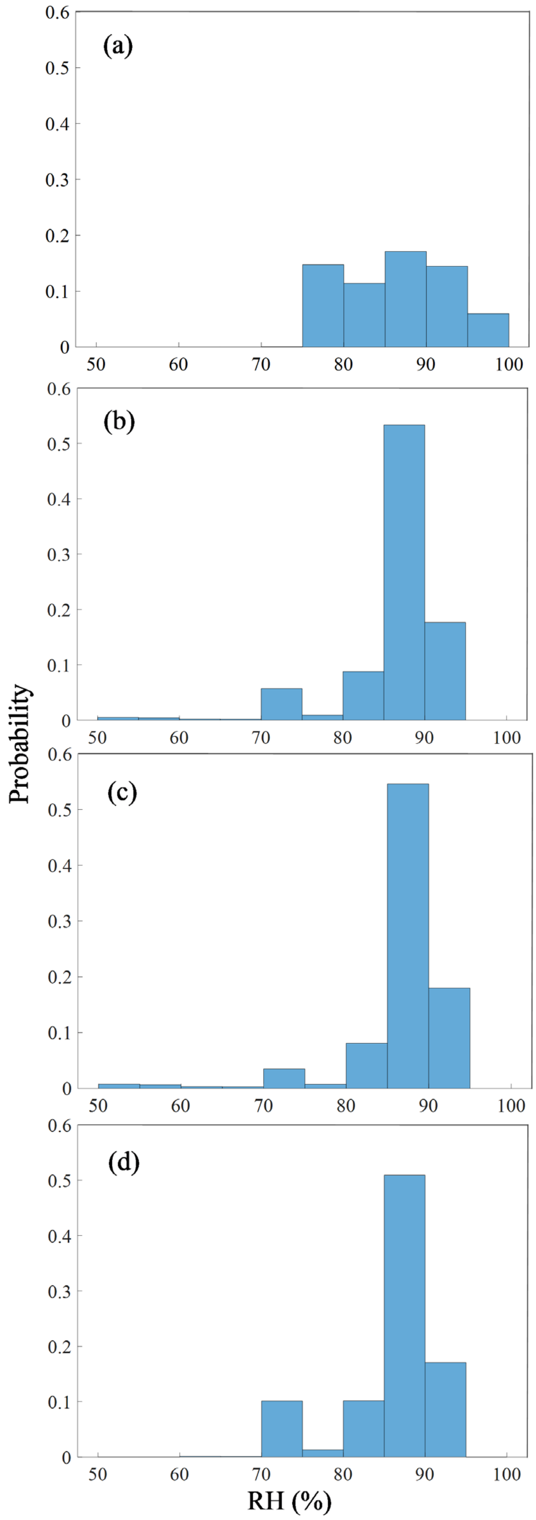

Figure 8. Probability distribution of the relative humidity RH during the experimental campaign. (a) nVW case; (b) VW case; (c) VW case when fans are activated; (d) VW case when fans are off.

Then, for each one of the considered conditions, the table presents the total number (n_{pass}) of exceeding conditions and frequency (F_{pass}) of the total number of exceeding conditions. Moreover, the table reports the number (n_1c) and the frequency (F_{1c}). Specifically, n_{1c} indicates the number of records of one condition when that condition is the

Table 3. Correlation matrix for fans 'on' (the values in the table represent the determination coefficient R^2).

	$H_{b,i}$	H_a	$\|H_a - H_r\|$	$\|T_a - T_r\|$	H_r	$H_a - H_r$	$T_a - T_r$
H_b	1.000						
H_a	0.351	1.000				Symmetric	
$\|H_a - H_r\|$	0.041	−0.795	1.000				
$\|T_a - T_r\|$	−0.081	−0.547	0.681	1.000			
H_r	0.651	0.175	0.355	0.199	1.000		
$H_a - H_r$	−0.174	0.708	−0.918	−0.599	−0.571	1.000	
$T_a - T_r$	0.081	0.547	−0.681	−1.000	−0.199	0.599	1.000

Table 4. Correlation matrix for fans 'off' (the values in the table represent the determination coefficient R^2).

	$H_{b,i}$	H_a	$\|H_a - H_r\|$	$\|T_a - T_r\|$	H_r	$H_a - H_r$	$T_a - T_r$
$H_{b,i}$	1.000						
H_a	0.845	1.000				Symmetric	
$\|H_a - H_r\|$	0.284	0.332	1.000				
$\|T_a - T_r\|$	−0.347	−0.673	−0.228	1.000			
H_r	0.790	0.818	0.113	−0.384	1.000		
$H_a - H_r$	−0.463	−0.357	0.139	−0.029	−0.830	1.000	
$T_a - T_r$	0.347	0.672	0.228	−1.000	0.384	0.029	1.000

unique cause for the fan activation, and F_{1c} is proportion of exceeding the total numbers of that specific condition (n_{1c}/n_{pass}). As an example, C_3 is the unique cause of fan activation (when all other conditions mark 0) in 80 737 measurements that represent 96.5% of the total exceeding C_3 (83644).

Finally, for each condition, the occurrence frequencies (F_t) are shown, as the only cause of turning on of the system, on the total amount of the considered data (i.e. 151 592 activations). It is remarkable to notice that the difference between the average RH of the barrels and that of the room (C_3) caused more than 50% of fan activation and occurs alone. Table 6 exhibits the most critical condition in nVW, which is the RH peak C_1 that occurs 186 504 times (172 790 + 13 461 + 253).

From comparison, it can be deduced the fans' activation eliminates the wall RH peaks, raising the average RH. This can be explained by the presence of RH sources (detected during further investigation suggested by this work), which generates an average RH increase.

Uniformity index

The uniformity indices (UI) and first and third quartile thresholds (Q) have been calculated for both VW and nVW portions, for Tand RH, and for the different conditions analysed in the work. Table 8 shows that the UI of nVW is always higher than the VW. The difference is more relevant for T than RH; however, these results confirm the previous considerations. The efficiency of the ventilation system, designed and built for the present application, is confirmed by the number of times the fans are turned off in the VW, which is lower than they should be in the nVW. In addition, the average standard deviations were calculated and are reported in Table 9.

The table clearly highlights the effectiveness of the system in both T and RH in accordance with the previous results. Specifically:

- T and RH trends appear more uniform in the VW portion. The SD of the T values is reduced up to 70%, whereas the reduction of the SD of the RH values is 14%;
- the effects on the T are remarkably higher; in particular, the T SD is almost one fourth in the VW if compared to the nVW case;
- values of T SD lower than 1°C and about 6.5% for RH indicate that the wine in all the barrels will age under similar conditions;
- as expected, in the VW case, that is, when the fans are activated, the SD for the T decreases considerably with respect to the nVW case;
- even if the fans are turned off, T and RH show a lower SD if compared to the nVW case. This can be seen as a further positive effect of the functioning of the ventilation system to maintain good conditions even after the fans have been turned off.

Table 5. Number of occurrences of the four conditions C_1–C_4 in the ventilated wall portion.

C_4	C_3	C_2	C_1	No. of occurrences
0	0	0	0	69 395
			1	39 403
		1	0	11 327
			1	17 206
	1	0	0	80 737
			1	2903
		1	0	4
			1	0

Table 6. Number of occurrences of the four conditions C_1–C_4 in the non-ventilated wall portion.

C_4	C_3	C_2	C_1	No. of occurrences
0	0	0	0	33 838
			1	172 790
		1	0	521
			1	13 461
	1	0	0	105
			1	253
		1	0	7
			1	0

Table 7. Number of occurrences for each critical condition.

Condition	n_{pass} (−)	F_{pass} (%)	n_1c (−)	$F1c$ (%)	F_t (%)
C_1	59 512	39.3	39 403	66.2	26.0
C_2	28 537	18.8	11 327	39.7	7.5
C_3	83 644	55.2	80 737	96.5	53.3
C_4	0	0	0	0	0

Table 8. Uniformity indices and first and third quartile thresholds for T and RH in the non-ventilated and ventilated wall portions.

		T (°C)			RH (%)		
Wall portion		UI	First quartile thresholds	Third quartile thresholds	UI	First quartile thresholds	Third quartile thresholds
Non-ventilated (nVW)		0.164	0.055	0.281	0.087	0.071	0.109
Ventilated (VW)	Fans on	0.045	0.026	0.054	0.079	0.021	0.085
	Fans off	0.046	0.034	0.058	0.082	0.081	0.085
	Total	0.045	0.026	0.054	0.079	0.021	0.085

Table 9. Average SD for T and relative humidity (RH) in the non-ventilated and ventilated wall portions.

Wall portion		T (°C)	RH (%)
Non-ventilated (nVW)		2.245	7.481
Ventilated (VW)	Fans on	0.598	6.428
	Fans off	0.680	7.026
	Total	0.646	6.488

The results show how the ventilation system can detect the most critical conditions and, overall, improve the uniformity of T and RH in a barrel. The indoor homogeneity helps to keep the wine under the proper environmental conditions for the ageing phase and can guarantee that all the barrels are maintained in similar conditions. This is an important aspect for the definition of standard wine quality.

Conclusions

The present paper concerns the study of a microventilation system in an underground cellar used for the ageing of wine in wooden barrels. The system is composed of T and RH sensors, fans and pipes for the ventilation and a central unit programmed to manage and record the data. In particular, the central unit manages the activation of two fans according to the overrun of set conditions related to T and RH close to the barrels. The system was installed for 1 year in a case study cellar, and the collected monitoring data were analysed. In particular, the system:

- is effective in identifying critical situations occurring in the cellar, thus allowing the owner to detect dangerous rising damp in the floor;
- is able to improve the uniformity of the air in the cellar according to the UI introduced here;
- is more effective in homogenising T than RH;
- cannot improve the overall T and RH of the cellar as its effect involves local rather than overall distribution of T and RH.

Moreover, besides the analysis of the standard deviation of the dataset, the UI proposed here could represent a useful tool to also evaluate the homogeneity of the dataset for different physical parameters (in this work, T and RH). In addition, the experimental campaign highlighted some issues that should be solved in future research and ventilation system development. Specifically:

- Because of the aggressive conditions of the cellar, the sensors installed for long period monitoring should be protected;
- In a regular cellar, a high number of sensors can represent a problem, and therefore, a procedure to identify the most proper sensor number and location must be considered once the efficacy of the system is verified;
- Because of the importance of the environmental conditions in the cellar, the system should be able to send alerts in real time to the personnel involved in the wine-ageing phases;
- Moreover, the possibility to check, in real time and remotely, the T and RH trend (by means of an internet cloud) must be implemented;
- The addition of an air conditioning system close to the inlet fans, able to provide average T and average RH control, should be considered.

Finally, the prototype showed promising results and, with further development, could become a valid and simple tool to check and manage wine ageing in existing underground cellars.

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