Numerical Analysis Of Micro-ventilation System In A Wine Cellar

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Abstract

The importance of internal environmental conditions in a wine cellar is well known and investigated. The process of wine preparation consists in several steps, where temperature and humidity play a fundamental role, since the quality of the final products is strongly affected by constant and suitable environmental conditions. However, various critical factors have emerged, such as mold growth or wine losses, where ventilation has proved to be insufficient or poorly designed. Considering these, the addition of a mechanical ventilation system, consisting in a perforated tube provided by a small fan, has been considered to support the possible lack of natural ventilation. The comparison between the two cellar configurations has been carried out through CFD modeling of the indoor air and temperature distributions in the room, in two different period of the year when the natural ventilation is differently performed.

Introduction

Since the past centuries, the research has been devoted to the definition of ideal room conditions for wine-aging process performed in wooden barrels. In literature, on this topic, it is possible to assess that the wine should be kept at a temperature ranging from 9°C to 20°C Troost (1953) and Vogt (1971) defined that an optimal thermal excursions smaller than 6°C and Togores (2003) considered that the relative humidity should be higher than 70 %, in order to ensure a quality aging and to prevent excessive wine loss due to evaporation. The wine losses has been considered as a function of air temperature and humidity. Negrè and Françot (1965) showed how high temperatures, as for example 18°C, and low relative humidity, 45%, could affect wine conservation, with losses of 7:4% in volume per year. Ruiz De Adana et al. (2005) developed a mathematical model that correlates

wine losses to the ambient conditions, thus quantifying how the air velocity, temperature and humidity can have an effect on wine evaporation. It is also suggested that low air velocity values could prevent excessive wine losses. Another important and critical aspect is the mold and other fungi formation, promoted by high level of relative humidity, which can contaminate and so affect the wine quality or its properties (Simeray et al., 2001). About the micro-climatic conditions of conservation, Ocon et al. (2011) presented the natural ventilation as an important factor to reduce the mold presence in the air, considering to decrease consequently the possibility of mold proliferation on the barrels. Despite this, in literature there are not many studies about the ventilation role in wine cellar indoor conditions. Moreover, the ventilation optimal standards are not well determined. In particular, Geyrhofer et al. (2011) defined a range of air velocity between [0.3 0.4 m/s] reachable with a conventional natural ventilation system. However, these air velocity magnitudes characterize all wine cellars and can be considered insufficient based on the previous issues presented. Due to these, could be useful to improve the air velocity magnitude around barrels in order to avoid mold formation but also with magnitudes such as not to increase wine losses, in specific limited to 1 m/s (Ruiz De Adana et al., 2005). In spite of the significant role of ventilation in the environmental condition in wine cellar, the application of CFD for improving the ventilation in this sector is really rare, compared to the greenhouses or livestock sectors. De Rosis et al. (2014) performed a numerical study of air flows in a wine aging-room, using a Lattice-Boltzmann method with the aim of underlining how barrels are differently involved in air flows and consequently with the aim of identifying the most emblematic points for air velocity control. In this paper, CFD simulations have been performed in order to evaluate the different air and temperature distribution in-

side a wine cellar, under two different ventilation configurations. In particular, in one of the two configuration has been added a mechanical ventilation system, previously designed and tested, to support the usual ventilation system (Santolini, 2019). Moreover, the goal is to observe if this mechanical system can lead to a more homogeneous indoor micro-climatic conditions and possibly consider further improvements to obtain a well distributed environment, through CFD modeling.

Material and Methods

The natural ventilation of a basement wine cellar consists in general in inlets, like windows and door, and outlets, such as one or more openings in the walls. The ventilation is carried out by the outside wind but also by the difference in temperature between interior and exterior environment. In this case, the case study presents a door, a window and three circular openings, as presented in Figure 1.

Figure 1: A 3D model of the cellar, carried out in AutoCAD, where are also showed the barrels placed along the walls.

At this general configuration, the addition of two mechanical ventilation systems has been considered behind the barrels located in the area on the side of the window. Similar systems are already applied for the ventilation in non-residential buildings but rarely in agricultural ones (few applications in livestock). This system consists in a perforated and closed PVC tube of 120 mm of diameter connected by a polystyrene junction to a PC fan of 220 V, which blows the air through the pipe. On the pipe, a line of 31 holes, equally spaced, of 0.005 m of diameter has been created. This system has been previously tested in terms of air flow characteristics and its CFD model has been validated by air velocity measurements. In fact, a prototype of the system has been performed and

the air velocity profile and magnitude obtainable have been tested and verified. In particular, the the distance of investigation has been 40 cm from the system (distance between the holes of the pipe and the center of the barrels) and the target air velocity have to be contained in the optimal range of 0.4-1 m/s. The air velocity at this distance has been detected around 0.5 m/s, within the defined range, as shown in Figure 2. Furthermore, the 3D CFD model of the wine cellar has been performed and validated, as reported in the section below (Santolini, 2019).

Figure 2: The velocity profile of the system and the relative averaged velocity are presented.

In this work, two systems have been considered placed in the wine cellar, behind part of the barrels, with the orientation of the holes not horizontal but oriented 45° one upwards and the other downwards, as shown in Figure 4. The comparison between the two configurations, without and with system implementation, has been performed considering four different initial conditions and two different ventilation set up, representative of two different periods of the year: the spring and the autumn. The environmental conditions for the simulations have been defined considering the data collected inside and outside the wine cellar during a year (2013). The data related to April and May have been used for the definition of the initial conditions of two cases for the spring season: the average conditions based on whole data of the two months and the extreme conditions, average of the data registered on the hottest day of the two months. Instead, the data of October and November have been considered for the definition of initial conditions of the autumn season's cases: the average conditions based on whole data of the two months and the extreme conditions, average of the data registered on the hottest day of the two months. About the ventilation, these two seasons present two different ventilation systems and approaches. In spring the window is usually

opened for the room ventilation, in order to have one or two air changes per day. Instead in autumn the window is rarely opened and the slight necessary ventilation is considered performed by means infiltration from the building envelope. In fact, the autumn ventilation configuration considers a natural ventilation possible thanks to the air passage through window and door frames, as explained in the section below. These two different ventilation cases have been taking into account as representative of the two seasons. The 3D CFD model of both cellar configurations has been obtained through geometrical modeling by AutoCAD, meshing process by ICEM CFD and fluid-dynamic simulation by Ansys-Fluent Inc. More detailed information about the modeling of these cases have been presented in the following sections.

Grid convergence study

The definition of the suitable mesh for the simulations has been obtained through a grid convergence study. Considering the characteristics of the geometry, unstructured meshes have been carried out. In particular, five progressively finer meshes have been prepared without supporting ventilation systems, from $4e^5$ to $5.3e^6$ number of cells.

Table 1: Boundary condition of the CFD models.

Parts of domain	Boundary conditions
Room walls	Walls
Window	Pressure-inlet or wall
Barrells	Walls
Holes	Pressure-outlets
Door	Wall
Frame infiltration	Velocity-inlet or Pressure-inlet
Pipe	Wall
Pipe holes	Interior
PC fan	Fan

The simulations have been performed as a steady-state calculation using the k-epsilon realizable, as turbulence model, and the Boussinesq model, in order to evaluate natural convection inside a closed domain. The boundary conditions have been defined as presented in Table 1. The air velocity has been fixed at 0.1 m/s only for the autumn cases, identifiable not only entering from the window but also from the door, modeled as a frame of 3 mm of width around the perimeter of the openings. The other surfaces, wall and barrels, have been modeled as walls.

The simulations have been performed with convergence criteria based on absolute residuals and the threshold for convergence has been set to 10^{-5}

Table 2: Boundary condition of the CFD models.

Period	T_{in} (K)	T_{ex} (K)	v_{air} (m/s)
Spring (averaged)	288.66	287.2	
Spring (extreme cond.)	291.66	301.66	
Autumn (averaged)	290.66	283.4	0.1
Autumn (extreme cond.)	287.66	297.66	0.1

for continuity and 10^{-7} for all other parameters, checking also the mass flow equilibrium. From the results of each simulation, six different velocity profiles have been chosen to calculate $\|L\|_{inf}$ (eq. 1) (Santolini et al., 2018; Magnini et al., 2016). In particular, three profiles have been considered at first pipe level at distances of 18, 40, 98 cm from the system. Other three profiles have been considered at the second pipe level at the same distances selected for the first three points.

$$\|L\|_{\infty} = \max(|v_a - v_b|) \quad (1)$$

From the calculation of $\|L\|_{inf}$ for each profile, between each mesh from the coarser to the finest, the averaged values of the norm has been obtained, as shown in Figure 3. The Figure 3 presents a progressively stabilization of the values from the $\|L\|_{inf}$ calculated between the second and the third mesh. In particular from this result, the mesh characterized by $2.7e^6$ number of cells has been chosen for the later simulations.

Figure 3: Comparison between results of the simulation, through the calculation of the $\|L\|_{inf}$, from the coarser mesh to the finest one.

Four different case studies have been investigated. Considering the spring period, the configuration without and with the mechanical ventilation systems have been simulated, such as the same for the autumn period. In the spring cases, the window has been considered opened and the indoor temperature has been defined as summarized in Table 2. In the autumn simulations, the window and door frame slots have been modeled as interior surfaces, which means open surfaces to the air flow, less than 1 % of the entire surface. The

initial conditions for the fan modeling have been obtained from the PC fan's data sheet: 45 Pa of static pressure, 2450 rpm of velocity, 0.06 m of internal fan body and 0.125 m of external diameter.

Figure 4: Frontal view of the 3D model of wine cellar, where the additional ventilation system are present.

In all the simulations, the convergence criteria have been maintained as the ones used for the convergence study.

Model validation

The validation process has been conducted by the comparison between the simulated results and the collected data in controlled conditions inside the wine cellar.

Figure 5: Velocity simulated profile is compared to the air velocity data collected in several positions at an height of 1.6 m.

In specific, during the measurements the window and the door have been kept closed and the holes opened. Moreover, a constant air velocity source (a fan) has been placed at the door position at 1.20 m. In order to conduct the comparison, 70 measurements points have been identified. Several velocity profiles at different heights have been compared to the measured data, such as the profile along the horizontal axis of the inlet along the central longitudinal axis of the cellar at height of 1.60 m, shown in Figure 5. The comparison between data shows a good agreement between measured and simulated velocities. Based on the 70 measurement points to validate the model, the overall RMSE has been evaluated of only 0.29 m/s.

Results and Discussion

The air velocity and the temperature distributions have been qualitatively analyzed. In particular, based on the period taken into account, the configuration without and with additional ventilation systems have been compared. The two horizontal planes at level of the ventilation pipes, at 0.8 m and 1.6 m of height from the floor, have been considered for the analysis. In Figure 6 and Figure 7, the air flow distributions of the spring case (averaged condition) is presented.

Figure 6: The contour velocity maps of the two spring simulations are compared by the sections at $z = 0.8$ m: (a) is the configuration without additional ventilation system, (b) is the configuration with supporting ventilation systems.

It is visible that the air velocity magnitude in absence of the additional ventilation system is significantly low in the barrels area, around 0.05 m/s in both planes. Then, the area around the barrels can be considered a stagnation area due to the negligible magnitude velocity, which can cause mold formation on the barrels, as a sign of bad wine conservation. On the contrary, the air velocity magnitude in presence of the additional ventilation systems is significantly higher in the same area. In fact, in both sections, the air velocity around the tube and the barrels goes from minimum values of 0.1 m/s to a maximum of 0.5 m/s. These air velocity magnitudes are ranged in the optimal wine conservation air velocity interval. Considering the temperature distribution, in these areas are no appreciable differences between the cases. The value of temperature inside the room is around 287.2 K, with negligible variations. For that, the analysis the analysis of the temperature

Figure 7: The contour velocity maps of the two spring simulations are compared by the sections at $z = 1.6$ m: (a) is the configuration without additional ventilation system, (b) is the configuration with supporting ventilation systems.

distribution is not reported. An interesting aspect of the ventilation air flow is related to the incoming flow from the window.

Figure 8: Comparison between velocity vector maps of the middle sections, of the spring simulations: (a) case without mechanical ventilation systems and (b) case with these systems.

In fact, the air enters in the cellar from the upper section of the window and also goes out from the bottom part of it, as shown in Figure 8. However, the air flow patterns are not the same between the two cases, which is likely due to the presence of the mechanical systems. In fact, the air jet entering in the room, without any systems, reaches the center of the wine cellar, creating a vortex that interest

the half of the wine cellar section, close to the window. On the contrary, the air jet coming in, in presence of the additional ventilation systems, has a shorter penetration distance in the room, affecting approximately half of the area interested by the air flow distribution of the previous case.

Figure 9: The image compares the contour velocity maps of the two autumn simulations by the sections at $z = 0.8$ m: (a) case without mechanical ventilation systems and (b) case with these systems.

In this case the vortex is also present but, compared to the previous case, at the floor level are visible higher velocity magnitude and variations of air velocity direction. The results for the autumn simulations (averaged conditions) are similar to the spring ones, as visible in Figures 9 and 10. In fact, the natural ventilation of the wine cellar is characterized by a stagnation area around the barrels. The Figures 9 and 10 show the presence of an air flow entering from the frame slots of the door, in both sections of the configurations. This slightly affects the air flow distribution close to the door, where the air velocity reaches magnitude between 0.1-0.2 m/s. The action of the ventilation pipes instead increases the air velocity around the barrels in both sections, extending the air mixing area, similarly to the previous cases. In this case, the evaluation of the temperature distribution has been investigated considering the differences in the distribution between the two configurations. In Figure 11 the contour maps of section $z = 1.6$ m are presented. It is clear that the range of temperature variation is wider in the section with the mechanical ventilation systems, from 283 K to 284.8 K. In the case without ventilation pipes, the side of the cellar at the right, after the separator

septum, is characterized by an higher temperature than the other part.

Figure 10: The image compares the contour velocity maps of the two autumn simulations by the sections at $z = 1.6$ m are compared: (a) case without mechanical ventilation systems and (b) case with these systems.

This can be due to the distance from the openings and consequently to the lower ventilation effect of the opening slots.

Figure 11: The image compares the contour temperature maps of the section at 1.6 m of the configurations without additional ventilation system ((a)) and with ventilation systems ((b)).

This condition is characterizing also the case with pipes ventilation system, in particular at section $z = 0.8$ m. In these sections an increased temperature around the ventilation systems area is visible. This fact could be attributable to the action of the ventilation system itself. However, from the comparison of these cases the temperature shows slightly different magnitude in the cellar but the distribution doesn't show significant variations.

Figure 12: The image compares the contour velocity maps of the two autumn simulations by the sections at $z = 1.6$ m are compared: (a) case without mechanical ventilation systems and (b) case with these systems.

Figure 13: The image compares the contour velocity maps of the two autumn simulations by the sections at $z = 1.6$ m are compared: (a) case without mechanical ventilation systems and (b) case with these systems.

Based on the data of the extreme conditions reg-

istered during autumn season, the simulation results of the two configuration of the wine cellar have been shown in Figure 12 and Figure 13. In this case, both section analyzed without additional ventilation system present a slightly higher air velocity involving all the room area; it is a limited improvement compared to the averaged case of the autumn season, dependent from the different initial conditions. Furthermore, the placement of the supporting ventilation system is giving similar results to the averaged case (see Figure 9 and 10) but the area of action seems to be wider, in synergy with the natural ventilation from window and door slots. The air velocity magnitude in the barrels area with the system is ranged in the optimal velocity interval for the wine conservation, with effects also in the area over the barrels.

Figure 14: The contour velocity maps of the two spring simulations by the sections at $z = 0.8$ m are compared: (a) case without mechanical ventilation systems and (b) case with these systems.

Considering the extreme spring case, the natural ventilation contributes more than other situations to room ventilation, as visible in Figure 15, particularly at the window's height. In fact the Figure 15 shows that the air flow from the window affects all the room area in front of the window, at the upper parts of the wine cellar. However, considering both sections (Figure 14 and Figure 15), the system has an important area of action, with higher air velocity magnitudes, compared to the previous cases. The air flow entering from the opening has indeed higher air speed than the other cases, due to the temperature difference between inside and outside. Moreover, in this case the system significantly changes the ventilation conditions, positively affecting not only the low-speed

areas nearby but also the center of the room and partly also the areas farthest from the window.

Figure 15: The contour velocity maps of the two spring simulations by the sections at $z = 1.6$ m are compared: (a) case without mechanical ventilation systems and (b) case with these systems.

However, based on all the simulation results, the right part of the room is characterized by the worst conditions for the wine conservation, caused by the inefficiency of the natural ventilation system configuration in both seasons. Comparing also the results obtained at different heights, in general the lower area, at 0.8 m of height, presents a much more disadvantageous situation compared to the higher section, at 1.6 m, both in the absence and in the presence of the system, although it certainly gives an improvement locally. In these environmental conditions, the lower part of the room is marginally affected by the ventilation action deriving from the window, so as to be considered an area at negligible air velocity (stagnation area) and therefore to improve for a good conservation of the wine.

Conclusions

The analysis of the air velocity and temperature distributions of the cellar cases have been conducted by a qualitative analysis, comparing contours and vector maps. The results have outlined that the natural ventilation of the wine cellar in spring and autumn (averaged and extreme conditions) is insufficient to ensure the optimal conditions around the barrels for the wine conservation. Moreover, it has been highlighted that the placement of the mechanical ventilation systems can have significant effects on the internal wine cellar conditions, mainly on the ventilation efficiency. In fact, the systems have proved to ensure

an improvement on the air velocity close to the barrels, where the ventilation conditions are more important for the wine conservation. The air velocity magnitude can reach higher values, limited to 0.3-0.5 m/s, which are considered an optimal range for wine ageing process. Then, this supporting ventilation system can be used for locally improving the air velocity, based on the needed conditions. Therefore, even from this preliminary work, the implementation of a well designed and optimized mechanical ventilation system in a wine cellar could be considered a strategy to obtain better internal climatic conditions for the wine conservation.

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