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# Numerical simulations of the airflows in a wine-aging room: A lattice Boltzmann-Immersed Boundary study

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ABSTRACT

In this paper, the airflows developing in a room devoted to the wine-aging process are numerically predicted. A real study case is investigated, regarding an Italian company operating in the wine sector. The airflow is modeled by adopting the lattice Boltzmann method. Specifically, large eddy simulations are performed through the Smagorinsky turbulence model. In order to account for the presence of walls and barrels, the Immersed Boundary method is used. Scenarios characterized by different layouts of the room are investigated, showing the incidence of an extra opening in the room on the whole air circulation. Present findings can be successfully used by wine-makers, since these provide the effectiveness of a numerical framework which predicts the developing of the airflow.



## 1. Introduction

Wine-making is a biochemical technique which transforms grapes into wine by performing a sequence of stages. Among these, one of the most interesting for chemists, microbiologists, wine-makers and even consumers is the wine-aging. Temperature and humidity play a fundamental role during the whole wine-aging process, since the quality of the final products is strongly affected by constant and suitable environmental conditions (Boulton et al., 1998). Since the past centuries, special attention has been devoted to the definition of ideal room conditions for wine-aging process performed in wooden barrels (Alberti, 1565). Recently, several authors focused on this topic, thus applying a scientific methodology to the process. Specifically, it is possible to assess that the wine should be kept at a temperature ranging from 9 °C to 20 °C (Troost, 1953; Marescalchi, 1965), thermal excursions should be smaller than 6 °C (Vogt, 1971) and the relative humidity higher than 70% (Togores, 2003), in order to both ensure a quality aging and to prevent excessive wine loss due to evaporation. Negre et al. (1965) studied the wine losses as a function of air temperature and humidity, showing how high temperatures, as for example 18 °C, and low relative humidities, 45%, can produce wine losses of 7.4% in volume per year. In a recent study, a mathematical model that correlates wine losses to the ambient conditions has been carried out, thus quantifying how the air velocity, temperature and humidity can affect wine evaporation (Ruiz De Adana et al., 2005). This model takes into account for the experimental evidence that the air velocity over the barrels affects the wood surface emission coefficient (Avramidis and Siau, 1987) and then the evaporation through the barrel stave. Therefore, the model suggests that low air velocity values can prevent excessive wine losses. According to Simeray et al. (2001), the relative humidity can favor mold and other fungi formation. This microbiological flora may potentially contaminate products or it can affect wine quality and organoleptic properties (Picco and Rodolfi, 2004). According to Ocón et al. (2011), the ventilation seems to be a fundamental factor to reduce the mold presence in the air, thus annihilating the possibility of mold proliferation on both walls and wooden surface of the barrels. Notice that the latter represents an ideal medium for mold proliferation (Navascues et al., 2001).

Summing up, besides temperature and humidity, the scientific literature highlights the relevant role of the air velocity in the wine-aging process. It is worth to notice that previous studies, carried out through numerical software, focused on the environmental conditions for wine-aging investigating temperature (Barbaresi et al., 2014) and humidity trends (Mazarrón et al., 2012) in wine-aging rooms. On the other hand, just few researches addressed issues concerning the air velocity (Ruiz De Adana et al., 2005). Therefore, herein we propose a methodology to compute the airflow in a wine-aging room. Then, such approach can converge in a cross-disciplinary research aimed at elucidating air velocity trade-off values which can reduce mold formation and, at the same time, can avoid excessive wine losses through evaporation. It is intriguing to highlight that the prediction of the airflows can be practically used to effectively design the ventilation systems in

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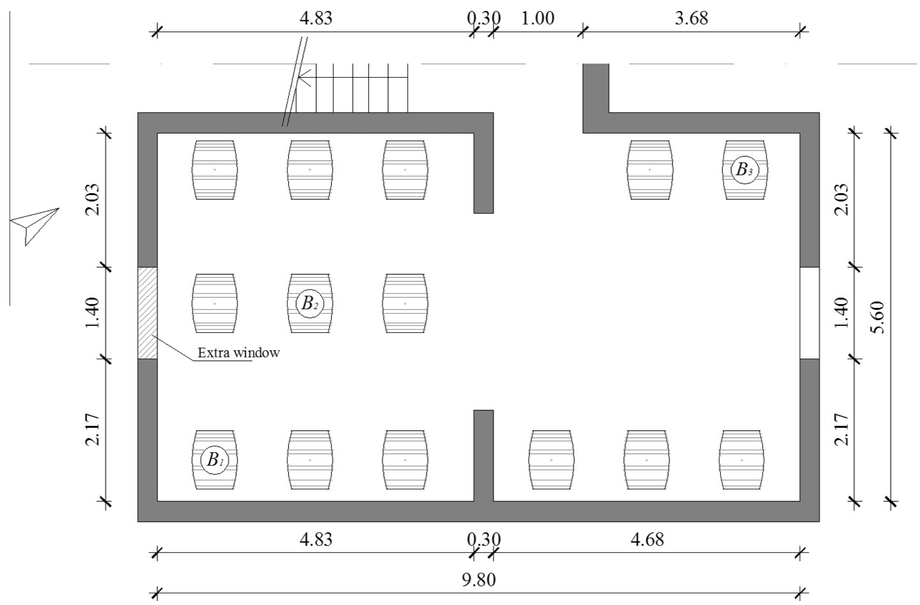


**Fig. 1.** Sketch of the cellar geometry.

order to maximize energy efficiency, to ensure high quality products and to reduce operating costs. Prediction methods, based on computational fluid dynamics (CFD) simulations, have already been successfully adopted for ventilation in greenhouses (Jiménez-Hornero et al., 2006; Bournet and Boulard, 2010; Boulard et al., 2010; Molina-Aiz et al., 2010), livestock (Bjerg et al., 2002), food-industry (Xia and Sun, 2002; Norton, 2013). Possible applications of CFD simulations in agricultural and environmental contexts have been underlined in Lee et al. (2013), while the usage of CFD for bioenergy and biomass has been highlighted in Bartzanas et al. (2013) and Wu (2013). Moreover, a review of numerical predictions of heat and mass exchanges at leaf surface has been carried out in Defraeye et al. (2013). In this work, the airflow in a room devoted to the wine-aging process is predicted by performing two-dimensional numerical simulation through the lattice Boltzmann (LB) method (Benzi et al., 1992; Chen and Doolen, 1998; Succi, 2001). This method has been preferred to standard continuum-based solvers due to several reasons. In particular, the authors remark that the method is intrinsically parallel scalable and highly computational efficient, especially if force computations are involved in the simulation. In order to account for the presence of obstacle in the fluid domain, i.e. the barrels in the wine-aging room, the Immersed Boundary (IB) method is adopted (Peskin, 2002; Fadlun et al., 2000; Wu and Shu, 2009). These two method are combined within a proper coupling strategy, whose effectiveness and accuracy properties have already been widely tested De Rosis et al. (2014c). A wide numerical campaign is carried out, focusing on the prediction of the airflow arising in a wine-aging room under the adoption of different layouts. Specifically, two macro-configurations are investigated by neglecting and accounting for the presence of an open window in the leftmost section of the domain. For a given macro-configuration, scenarios characterized by the presence and absence of a door are investigated. Moreover, further simulations are carried out by placing and removing barrels in a portion of the room. Findings are presented in terms of time history of the velocity computed for three different barrels, each one characterized by four different checkpoints. This aim of this choice is to elucidate that barrels are differently involved by the airflow. Moreover, a barrel can experience velocity values which can be drastically different along its own perimeter. Therefore, the adoption of only one representative point for a barrel can be cumbersome. Present findings show that the adopted numerical strategy is effective and accurate for computing the airflow in a wine-aging room.

The paper is organized as follows. In Section 2, the study case is presented, together with the definition of the problem. In Section 3, findings from a numerical campaign are discussed. Some conclusions are drawn in Section 4. Finally, a convergence analysis is shown in Appendix A.

## 2. Materials and methods

### 2.1. The case-study

The room (see Fig. 1) is a north-east oriented parallelepiped, 9.80 m long, 5.20 m wide and 2.60 m high. A horizontal cross section located at a height of 1.60 m is investigated. The room has a window and a door located at the north-east wall and at the north-west wall, respectively. No artificial ventilation system is provided, thus the cellar is naturally ventilated. Usually, the barrels are placed on holders located along the perimetric walls. If all such holders are filled, additional barrels are located in the center of room in the south side. A weather station is located 100 m far from the wine-aging room. It has recorded the wind speed direction twice per hour throughout one year. The door and the windows are closed in order to improve the indoor thermal stability and to protect the barrels from airflows. A monitoring system is installed

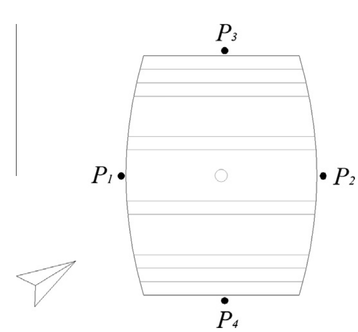


**Fig. 2.** Checkpoints.