Numerical simulation of the circulation of wine in tanks of different shapes

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Introduction

Winemakers started using amphorae (large jars) to mature wine in 2004. Made of terracotta (clay) or concrete, they encourage micro-oxygenation and other physical and chemical interactions in wine. The technique was hardly new: jars of different and complex shapes were used to store food in Gallo-Roman times.

According to an article entitled "The return of wines matured in amphorae" in the November 2011 issue of French wine magazine *La Revue des Vins de France* [4], "all those who use [amphorae] emphasise their potential for controlled oxygenation, linked to their porosity. Their rounded shape, assumed to help the liquid circulate and to create internal currents, is another factor."

"Assume" is the operative word here, since storage or vinification tanks do not easily lend themselves to observation. Measurement is intrusive, which makes numerical simulation essential in order to determine how wine circulates in these differently shaped containers.

In this paper, we take a look at the circulation of wine in three particular forms of concrete tank: Dolia, ovoid and elliptical.

For the simulations, we chose to model the tanks and then carry out a direct numerical simulation by solving Navier-Stokes equations. The results show that the intrinsic characteristics of the fluid and the material are relevant, without giving any consideration to the chemistry.

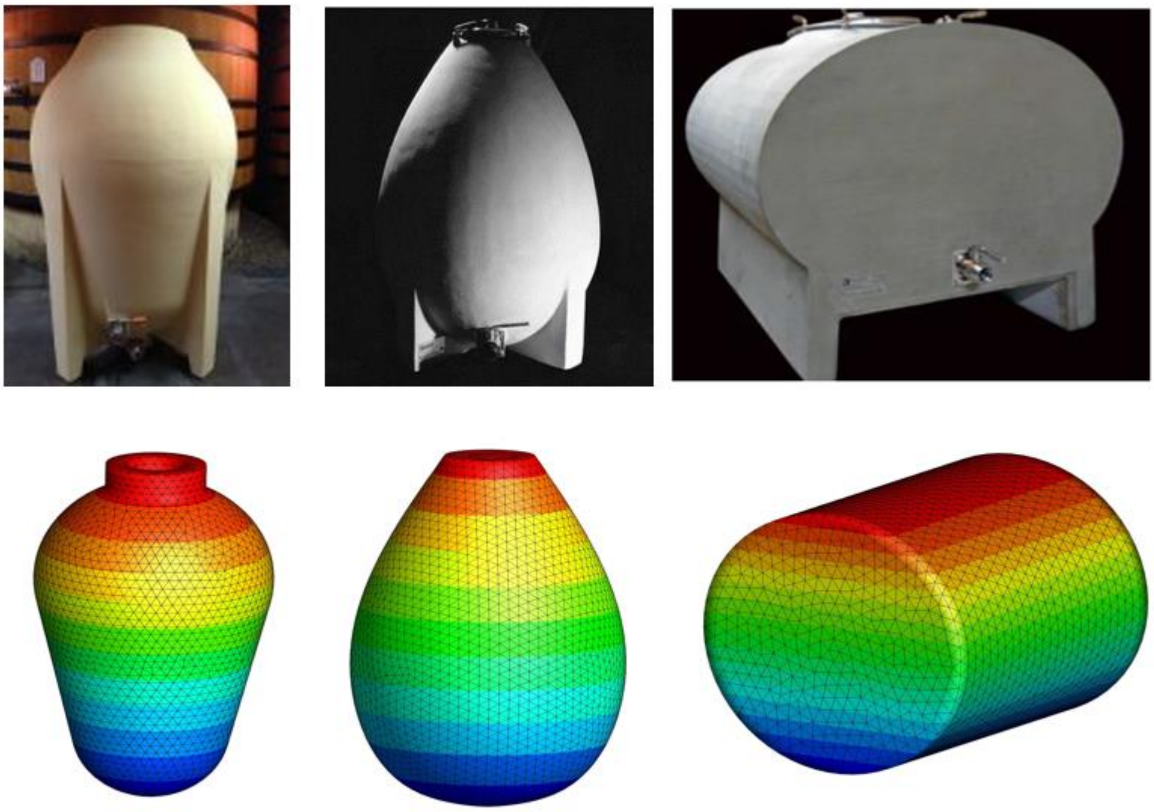
This study shows how wine circulates naturally in such tanks, without mechanical stirring, and in doing so provides input for the optimisation of existing methods. Numerical simulation appears to be the approach best suited to the creation of new solutions.

Modelling

The study concerns standard shapes of concrete tank [1,2] in use at various wine estates around the world. Through numerical simulation, it shows the internal currents which occur within them.

The standard shapes correspond to objects with a clearly defined curvature. The curvature of the Dolia tank, based on examples of storage jars used in Roman times, is defined empirically. Well-known equations are used to calculate the curvature of the ovoid and elliptical tanks.

The curvatures add a level of complexity to the solution of the Navier-Stokes equations, meaning that a refined mesh at the wall is necessary in order to obtain accurate results.



Dolia Tank **Ovoid Tank** **Elliptical Tank**

Figure 1. Representation and modelling of the tanks

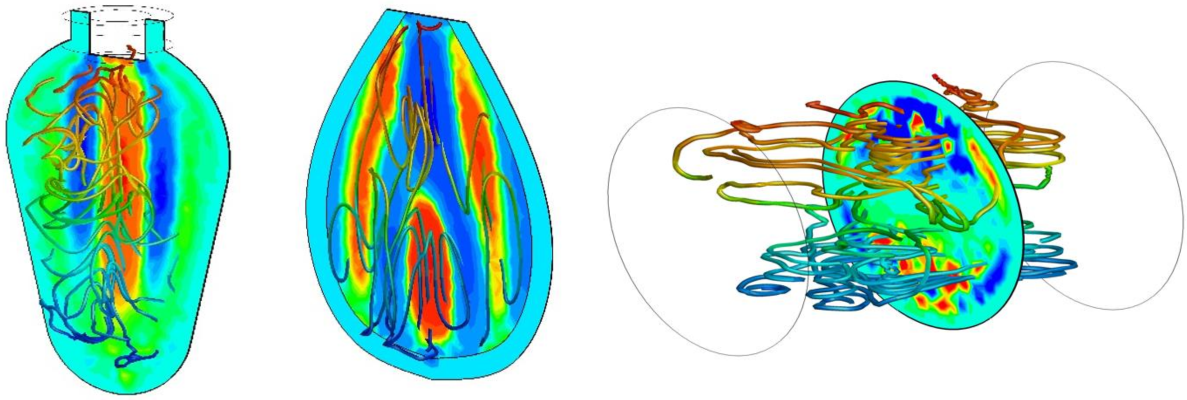
CAD software was used to model the tanks and industrial software to develop the mesh (Figure 1), taking precise account of both the shape of the object and the boundary layer close to the wall. The energy equation (temperature) is solved according to the intrinsic characteristics of the fluid and the material (Table 1).

Table 1: Simulation parameters	
General	
Gravity	9.81 m.s^{-2}
Temperature gradient	3° C
Fluid	
Density	0.998 kg.m^{-3}
Viscosity	10^{-3} kg.m^{-1}.s^{-1}
Thermal conductivity	0.5 W.m^{-1}.k^{-1}
Material	
Concrete: density	2200 kg.m^{-3}
Concrete: thermal conductivity	1 W.m^{-1}.k^{-1}
Stainless steel: density	7500 kg.m^{-3}
Stainless steel: thermal conductivity	26 W.m^{-1}.k^{-1}
Oak: density	800 kg.m^{-3}
Oak: thermal conductivity	0.16 W.m^{-1}.k^{-1}

The temperature gradient here corresponds to the difference in temperature between the top and the bottom of the tank generally observed in vinification vats.

Results

The simulations were carried out in 3D by computation and, within a few hours, produced the results shown in Figure 2.



Dolia Tank **Ovoid Tank** **Elliptical Tank**

Figure 2. Numerical simulation (Aquilon, [3]) of the tanks: vertical velocity is shown in the direction of gravity (red: positive, blue: negative)

The terrestrial reference frame is used for the experiment, hence involving gravity. Consequently, red indicates a positive velocity (top to bottom) and blue a negative velocity (bottom to top) in relation to the reference frame. The internal current is shown in 3D by the flow streamlines, which highlight the unsteady flow of the wine in these tanks. The thermal gradient on the gravitational axis remains virtually constant and is hence not the driver of the circulation.

The circulation is therefore caused by the low thermal gradient, which operates from the wall towards the centre of the tank (Figure 3), creating a velocity. The movement depends mainly on the curvature and the difference in thermal conductivity between the wine and the concrete.

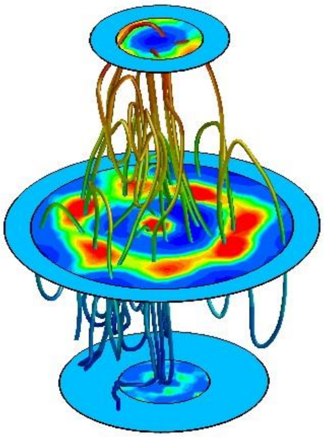
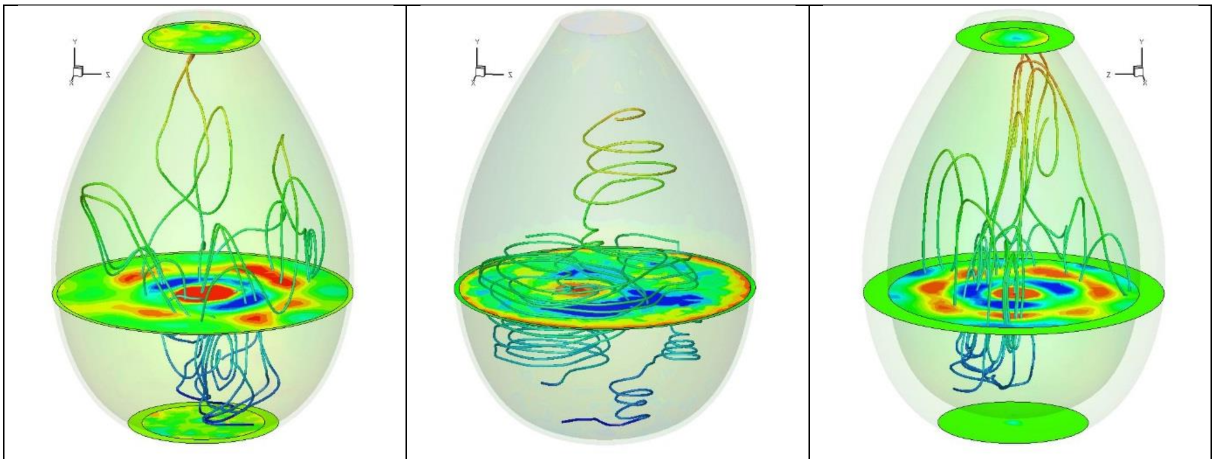


Figure 3. Numerical simulation (Aquilon, 4) of the ovoid tank. The radial velocity is shown in the direction from the wall towards the centre (red: positive, blue: negative).

Consequently, the wine circulates naturally, without any mechanical assistance, at velocities of the order of a micrometre per second, represented by the colour on the images above. Over a day, the distance travelled is 86.4 cm in a Dolia tank, 51.9 cm in an ovoid tank and 17.3 cm in an elliptical tank. Curvature therefore appears to be the key parameter in controlling the circulation of wine in tanks of different shapes.



Stainless steel ovoid	Oak ovoid	Concrete ovoid

Figure 4: Numerical simulation (Aquilon) of the ovoid tank in three materials. The colours show the velocity (red: positive, blue: negative).

In the case shown in Figure 4, we determined the shape of an ovoid tank and changed the material. For each material, we used thicknesses representative of real tanks: 1 mm for stainless steel, 4 cm for oak and 10 cm for concrete.

Over a day, the distance travelled by the wine is 69.12 cm for stainless steel, 51.9 cm for concrete and 17 cm for oak.

The greater the conductivity of the material, the greater the distance travelled. However, a high level of thermal agitation does not imply rapid homogenisation.

This slow movement ensures renewal of the boundary layer*, thus favouring micro-oxygenation due to the porous nature of the material.

**When a fluid flows along a fixed wall, the velocities at the wall are zero. The variation of its thickness depends on the viscosity of the fluid, which causes friction between neighbouring layers: the slowest layer tends to slow down the fastest layer which conversely tends to accelerate it.*

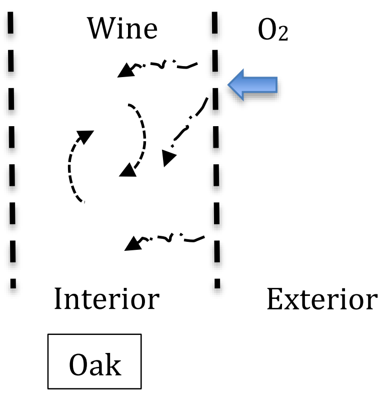
Discussion

Vinification

The shape is important for the formation of the cap. An ovoid shape, narrow at the top, creates a thick cap with little contact surface; as a result there is little exchange between the wine and the cap, so that more pumping-over is needed in order to soak the cap and extract the tannins.
In contrast, a shape with a wider top like the Dolia amphora creates a less thick cap for the same amount of material, thus increasing the contact surface. On pumping-over, the liquid spreads over the entire surface because the penetration time is shorter.
The circulation velocity of the liquid is greater in the amphora than in the ovoid. Consequently, exchanges are optimised between the liquid and the wall and between the liquid and the underside of the cap.
Concerning the choice of materials, stainless steel, on account of its high thermal conductivity, is sensitive to all temperature variations, directly creating internal currents.
With oak, whose conductivity is 200 times less that of stainless steel, the reaction time is sufficiently long for temperature variations close to the container not to interfere with the processes under way.
Concrete comes somewhere between the two. It is relatively insensitive to rapid variations in temperature but a constant gradient will trigger a movement of the liquid in the tank.

Maturing

The shape of the tank is chosen according to the intensity of the desired movement of the wine in the tank without mechanical assistance and must be combined with the choice of material. The supply of oxygen is the factor to be controlled during maturing. Stainless steel tanks are not porous and the wine is never static. Let us look therefore at the other two materials, concrete and oak. Concrete creates a movement in the tank which renews the boundary layer and hence causes a greater interaction between oxygen and the wine. Oak conveys a certain quantity of oxygen to its interface which then circulates in the centre.



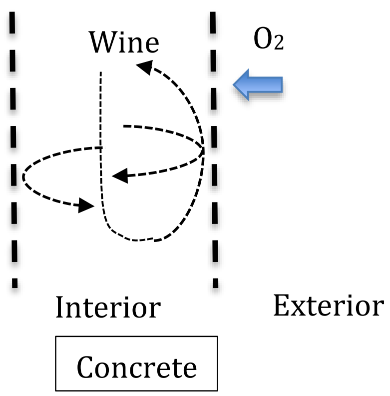


Figure 5: Schematic representation of how oxygen enters the wine depending on the material. Left, oxygen penetrates by diffusion (oak); right, oxygen is integrated by convection (concrete).

Wine estates are starting to vinify and/or mature their wines in Dolia or ovoid concrete tanks. They use these methods in order to avoid over-oaking. Some, like Château Pontet Canet [2], vinify their wines in oak vats then mature them in concrete amphorae, while others both vinify and mature their wines in concrete ovoid tanks or terracotta amphorae* in order to preserve all the fruit aromas and flavours (Domaine de Viret [5]).

**The thermal conductivity of terracotta is of the order of 0.3 $W.m^{-1}.k^{-1}$ with a high degree of porosity.*

Conclusion

When designing a variable-geometry tank, it is therefore essential to consider both its curvature and the intrinsic characteristics of the material used (density, porosity and thermal conductivity) in order to control its interactions with the fluid, both thermal and chemical.
From a physical standpoint, concrete seems to offer a good compromise in relation to oak or stainless steel.
Thus, depending on the use to which the tank is to be put, the balance between geometry, physics and chemistry is essential.

Outlook

Numerical simulations are a modern and flexible tool which can be used to modify the curvature very quickly and understand the physical mechanisms at work within the tanks. They may take account of many other phenomena, such as chemical kinetics, fluid-fluid interactions, fluid-particle interactions and hydraulics. Thus, they may also be used to optimise other processes such as bottling and filtration.

Acknowledgments

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References

1. http://www.cuves-a-vin.com/
2. Château Pontet Canet (http://www.pontet-canet.com)
3. Aquilon, numerical simulation software developed by J.P. Caltagirone.
4. "Modernité, le retour des vins élevés en amphores", *La Revue des Vins de France* no. 556, November 2011, pp. 30-36.
5. Domaine de Viret (http://www.domaine-viret.com)