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MODELLING WATER MIXING AND RENEWAL IN STORAGE TANKS

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Abstract

The current paper aims at presenting the main developments and achievement attained in research project IMiST which aimed at a better understanding of flow dynamics inside water supply systems' storage tanks to find practicable solutions to improve the design and the rehabilitation and to support operation of the existing tanks. The project comprised the development of an extensive experimental programme in small-scale models, full-scale testing in a real storage tank and advanced numerical modelling. Small-scale tests were carried out in the Laboratory of Hydraulics and Water Resources of Instituto Superior Técnico, Portugal, for different tank configurations and operating conditions. Two cross-section tanks (circular and rectangular) were tested with and without interior structures (baffles), with the inlet and outlet pipes at different locations and for constant and variable water level. Three sets of experimental tests were carried out using different instrumentation to collect complementary data, namely traditional tracer tests, dye tracer tests and velocity field measurements by Particle Image Velocimetry (PIV). A methodology for assessing mixing conditions in full-scale storage tanks was developed and tested in a real tank with a rectangular cross-section and 3500 m3 capacity with inner baffles. Advanced numerical modelling using Computational Fluid Dynamics (CFD) was carried out for the submerged and plunging get in a circular tank for betted understanding the velocity fields and the flow patterns. This complementary experimental and numerical modelling have allowed drawing conclusions concerning improving mixing measures, by readjusting the tank configuration (e.g., location, number and diameter of inlet/outlet pipes, jet inflow, fluctuating stored water volume and geometry) and changing operating conditions (e.g., extreme tank levels). New knowledge on water storage tank hydrodynamics has been created and recommendations for improving water mixing in existing tanks are briefly summarised herein.

Keywords
Storage tanks, water mixing, water renewal, water quality, experimental tests, CFD, PIV, improvement measures.

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1 INTRODUCTION

Water storage tanks are essential components of water distribution systems. These infrastructures are designed and operated to meet the variation of water demands of the distribution systems, while equalizing pressure and providing emergency storage. Nonetheless, they are also frequent sources of deterioration of drinking water quality, owing to inadequate tank design, operation and maintenance [1-2]

Typically, tank design does not account for water mixing and renewal. Tanks with inlet/outlet via single or adjacent pipes are common solutions in engineering practice, thus with bulky dead zones with minimal or null renewal [1, 3-4]. As large volumes are stored to respond to fire fighting and emergency demands, tanks are generally operated with high water levels with small amplitude draining/filling cycles. In addition, owing to temperature differences between inflowing and stored water, thermal stratification can be established, which can lead to ineffective mixing and stable stratified conditions [5-7].

Short-circuiting, zonal recirculation and thermal stratification allow for excessive residence times, particularly high in low or no flow zones with increased chlorine decay, biofilm development and sediment accumulation [1, 8-11]. In these circumstances, formation of potentially carcinogenic toxic disinfection by-products occurs, as increased amounts of chlorine are consumed, including those additionally added upon necessary re-chlorination [12-19]. Concomitantly, the existence of biofilm and sediments in a low or null chlorine concentration environment is a prone situation for microbial regrowth and associated risks, as well as for appearance of microbial taste and odour compounds [2]. In addition to the microbial regrowth upon re-suspension, accumulated sediments increase risks of discolouration in downstream pipes [9-11, 20-25]. Therefore, deficient mixing also leads to increases in frequency of required tank cleaning and disinfection [2, 13, 16-18, 26]. Improving mixing and reducing heterogeneous ageing and stagnation in storage tanks is, thus, crucial for the quality and safety of drinking water in supply systems.

Storage tanks have various cross-section shapes (e.g., rectangular, circular), sizes and inlet/outlet configurations (e.g., one single pipe for inlet and outlet, separated pipes located near each other or in extremities). Water flow paths and velocity and, thus, the prevalence of mixed or plug-flow regimes within the tanks, will depend on the tank configuration and operating conditions. Plug flow regimes are to avoid as tanks operated under these conditions tend to lose more disinfectant [27] and entailed mixing is minimal comparatively to mixed flow [2, 27]. On the other hand, the inclusion of baffles does not provide proper mixing and, generally, worsens storage tanks water quality [16, 27-30]. Water thermal stratification can even change the flow regime from mixed to plug-flow [31]. Tanks are normally operated without any active mixing devices, such as turbines or impellers [32], although mechanical mixing have been prescribed in particular situations [2]. Hence, mixing in storage tanks depends on water movement during the filling/draw cycle, i.e., on the kinetic energy of the inflowing water jet [4, 27]. Thus, effectiveness of mixing is mainly dependent on the inlet flow momentum (determined by inlet diameter and flow rate) and inlet location and orientation [33-36], as well as on tank geometry and size [27], though mixing dependence on various geometric parameters is not fully known [36]. Hence, tank water mixing and age, and, thus, quality and safety, do not depend exclusively on storage tanks characteristics and condition. They are also influenced by the fluctuations of inlet water flow and levels [37], as determined by volumes stored for emergency and demand management, and draining/filling times and frequency according to serviced areas consumption profiles. Nevertheless, water level in tanks and filling frequency are most frequently a function of electricity tariff schemes, as there is an emerging trend to minimize energy costs by scheduling pumps' operation [38-39]. Such operational decisions are made disregarding potential impacts on water mixing and turnover associated matters.

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Mathematical and physical models of mixing and water quality dynamics have been used to determine how alternative designs or operational policies affect the quality of water within the tanks [3, 8, 32, 40]. In this context, Computational Fluid Dynamics (CFD) modelling is a proven tool for describing flow fields in tanks, thus allowing to simulate different designs, configurations and operational conditions, in order to optimize mixing and residence times distribution [41-45]. However, due to the large variety of existing tanks sizes, shapes and configurations, only a small number of conditions have been studied. Most studies focused on a single factor (e.g., inlet flow location; tank shape) not integrating other critical and overlooked variables (e.g., varying stored volumes, tank filling/discharging flows; operating rules), nor testing single or combined mixing improvement measures. In addition, most CFD models lack experimental calibration and validation.

The current paper aims at presenting the main developments and achievement attained in research project IMiST – Improving mixing in Storage Tanks for safer water supply, funded by Fundação para a Ciência e Tecnologia, carried out between 2018 and 2022. This project aims at understanding flow dynamics inside storage tanks to find practicable solutions to improve the design and rehabilitation and to support operation of the existing storage tanks. The project, comprising advanced numerical modelling and lab and full-scale testing, innovatively includes velocity fields' measurement in laboratory tanks of different configurations and operating conditions by Particle Image Velocimetry (PIV). Likewise, mathematical modelling hydrodynamics are carried out by using Computational Fluid Dynamics (CFD). Improving mixing measures, by readjusting tank configuration (e.g., location and number of inlets/outlets, jet inflow, fluctuating stored water volume and geometry) and changing operating conditions (e.g., extreme tank levels, pump scheduling) are evaluated both experimentally and numerically for their effectiveness. Complementarily, the effect of implementing multiple or moving inlets on mixing at several filling levels is analysed. A methodology for assessing mixing conditions in full scale storage tanks is developed and tested. In addition to new knowledge on storage tanks hydrodynamics, outcomes include recommendations for upgrading tank design, rehabilitation and operation with measures for the improvement/rehabilitation of existing storage, as integrated on the normal or adjusted operation and configuration of the overall supply systems.

IMiST project is organized in seven main tanks: T1 - Field survey and database assembly; T2 - Lab scale studies; T3 - Numerical modelling; T4 - Full scale studies; T5 - Mixing improvement measures; T6 - Modelling of mixing in hydraulic simulators; T7 - Recommendations design, operation and rehabilitation. Results have given rise to several publications [46-51]. Relevant results attained in tasks T2-T6 are briefly presented herein.

2 SMALL-SCALE TESTING: TRACER TESTS

Small-scale testing aims at analysing the effect of the tank configuration and the operating mode on water mixing and renewal processes in two cross-sections (circular and rectangular) storage tanks of typical configurations in Portugal, operated at steady-state and at variable water-level. Experiments were carried out in a laboratory facility, assembled at the Laboratory of Hydraulics and Water Resources of Instituto Superior Técnico, Portugal. This facility was designed to develop tracer tests (Figure 1a) and determine the water residence time distribution (RTD). The tank was supplied by gravity fed with a tracer solution from two secondary tanks. Step input tracer tests consisted of continuously injecting a NaCl solution (0.05 gL^{-1}) at the inlet of the tank and monitoring the tracer concentration at the tank outlet. A control valve located immediately upstream of the tank regulated the inflow rate.

The small-scale tanks used are in 1:100 circular cross-section tanks of acrylic with 392 mm diameter and a maximum water-depth-to-tank-diameter ratio of 0.15; and 1:77 rectangular tanks square cross-section (350 x 350 mm^2), with a maximum water depth of 70 mm (corresponding to a maximum depth-width ratio of 0.2). Three different inlet/outlet pipe configurations were tested for the circular tanks (Figure 1b) and two configurations for the rectangular tanks (Figure 1c). Different inlet flowrates were tested for a constant water level (i.e., Q1=5 l/h, Q2=7 l/h, Q3=9 l/h and Q4=11 l/h) and for a variable water level (i.e., constant inlet flow 9 l/h and three outlet flow rates Q1=1.5 l/h, Q2=3.0 l/h and Q3=4.5 l/h) to simulate the fill-and-draw cycles in real tanks.

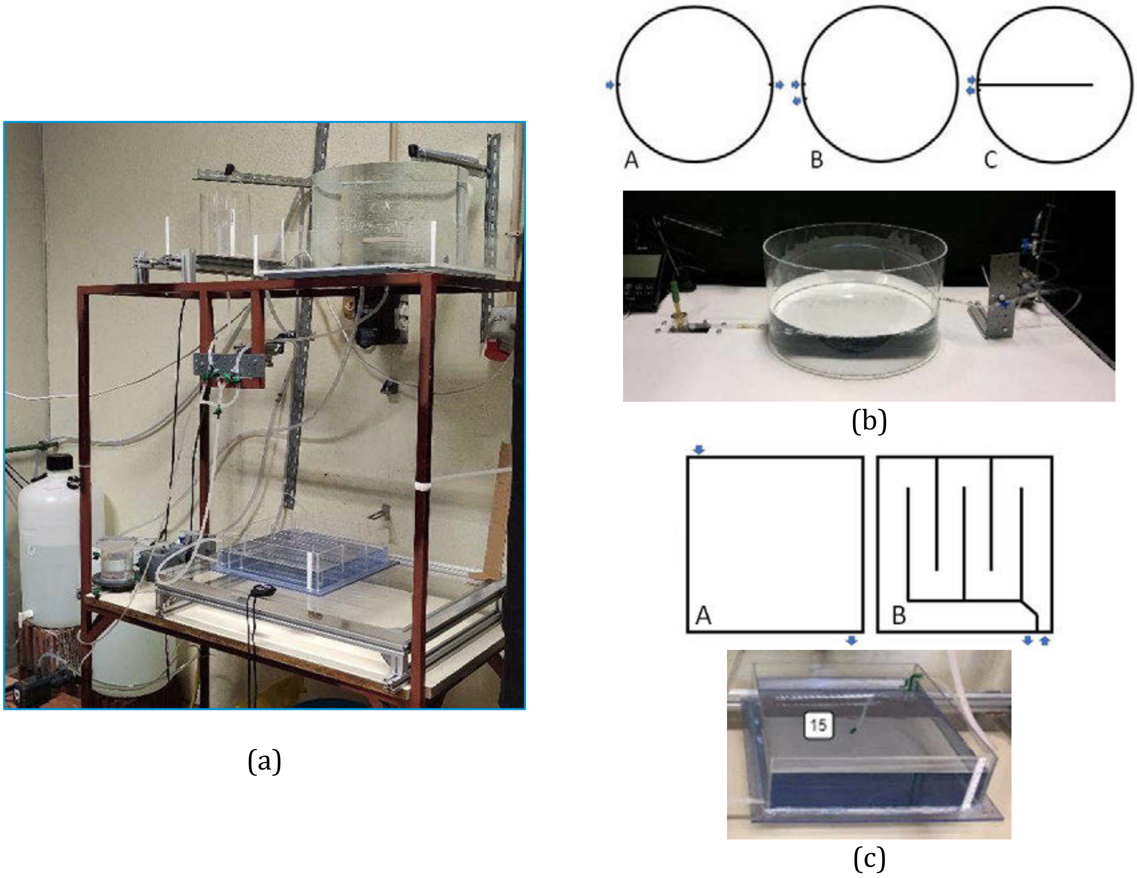

Figure 1. Small-scale test facility: (a) general view: (b) circular cross-section tanks; and (c) rectangular cross-section tanks.

The testing procedure was the following: i) the tracer concentration in the outlet pipe is measured along time, *C(t)*, and ii) measured values are normalized to obtain the non-dimensional cumulative distribution function $F(t)= C(t)/C_0$, where C_0 is the tracer concentration in the inlet pipe; iii) residence time distribution (RTD) function, *E(t)*, is calculated by differentiating *F(t),* representing the time spent by the different fluid elements inside the tank; iv) several hydraulic indices are calculated, namely Short-circuiting time (t_{10}), Morrill index ($Mo = t_{90}/t_{10}$) and the turnover/renewal time (t_{95}).

Circular cross-section tanks

The effect of inflow momentum flux on mixing in circular cross-section tanks is assessed by comparing the distribution curves (Figure 2) and the mean residence times (t') for flow rates *Q1* to *Q4*. The normalized RTD functions at different inlet flow rates present similar profiles, showing that the tested momentum flux range did not significantly change mixing within the tanks, except for Configuration A where the first peak increases with the flow rate. Increasing the flow rates makes the mean residence time (t') to approach the theoretical value (τ) because of diminished dispersion effects. In contrast, in Configuration B, a large part of the fluid entering the tank leaves almost immediately, which results in a mean residence time lower than τ. In the baffled tank (Configuration C), the mean and the theoretical values are very similar.

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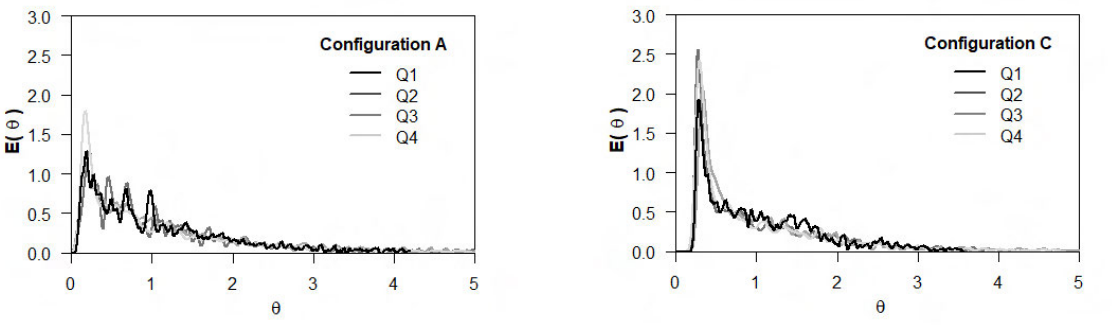

a) b)

Figure 2. Exemples of normalized residence time distribution for constant water level and for different flow rates: (a) configuration circular A; b) Configuration circular C.

Short-circuiting and mixing indexes for the three tanks at steady-state conditions are presented in Table 1. Configuration B shows the lowest t_{10} values. 10% of the injected tracer reaches the outlet pipe very quickly, in less time than needed for the same amount of tracer to leave a CSTR, denoting short-circuiting. For the higher flow rates (9.2 and 11.6 Lh^{-1}), t_{10} is lower than half of a completely mixed tank. For Configuration A, t_{10} is higher than for the CSTR, because of recirculation within the tank. This index presents the highest values for the baffled tank, much higher than those for the completely mixed tank. In Configuration B, $\bar{\sigma}$ is also the highest observed, which indicates that flow paths within the tank are quite diverse; yet, other indexes indicate that mixing is far from perfect. Configuration A shows high dispersion indexes, reaching values close to 1 and, thus, close to perfect mixing. *Mo* values range from 11 to 18, which is close to the ideal value of 22. Configuration C presents the lowest $\bar{\sigma}$ and, thus, the lowest degree of mixing. The Morrill index also shows that a lower degree of mixing is achieved in the tank with the baffle (Conf. C) than in the one without the baffle (Conf. A), as *Mo* are lower for tank C.

Table 1. Hydraulic indexes for the three circular cross-section configurations in steady-state conditions.

Config.	Q (L/h)	τ (min)	t' (min)	t_{10} (min) [θ_{10}]	t_{95} (min)	$\bar{\sigma}$ (-)	Mo (-)	t_{10} CSTR (min)	t_{95} CSTR (min)
A	5.1	85.2	87.7	16.5 [0.19]	264	0.7	12	9.0	255
	7.4	58.7	61.1	12.3 [0.21]	180	0.8	11	6.2	176
	9.4	46.2	47.3	8.5 [0.18]	147	0.8	18	4.9	138
	11.6	37.5	37.7	6.1 [0.16]	116	0.9	15	4.0	112
B	5.4	80.5	76.4	8.0 [0.10]	328	0.9	27	8.5	241
	7.4	58.7	54.7	4.4 [0.08]	258	1.0	36	6.2	176
	9.2	47.2	44.1	2.6 [0.06]	211	1.1	46	5.0	141
	11.6	37.5	33.9	1.4 [0.04]	140	1.1	70	4.0	112
C	5.2	83.6	83.4	24.7 [0.30]	240	0.5	8	8.8	250
	7.3	59.5	59.0	16.2 [0.27]	162	0.6	8	6.3	178
	9.1	47.7	48.8	15.3 [0.32]	132	0.7	7	5.0	143
	11.6	37.5	36.2	10.3 [0.27]	96	0.8	7	4.0	112

Three levels of variation in tank volumes were tested (20%, 50% and 80%) and an outflow pattern was used (Figure 3) to simulate real water storage tanks conditions. The inflow rate was either 9.0 Lh-1, during the filling period, or null, while the water level was decreasing.

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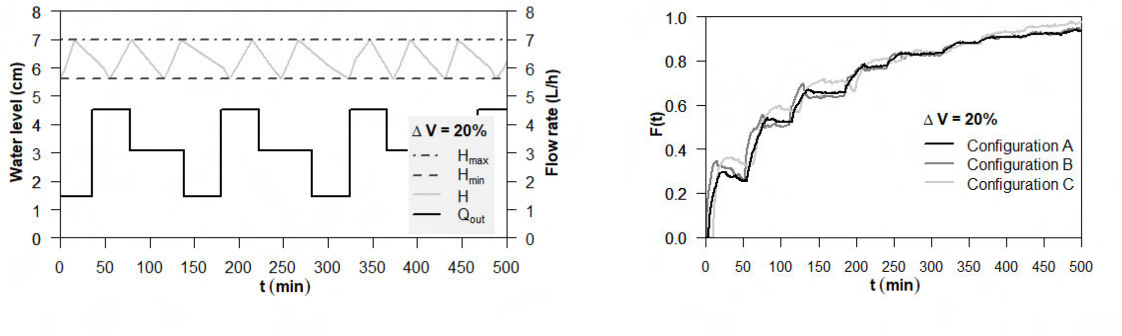


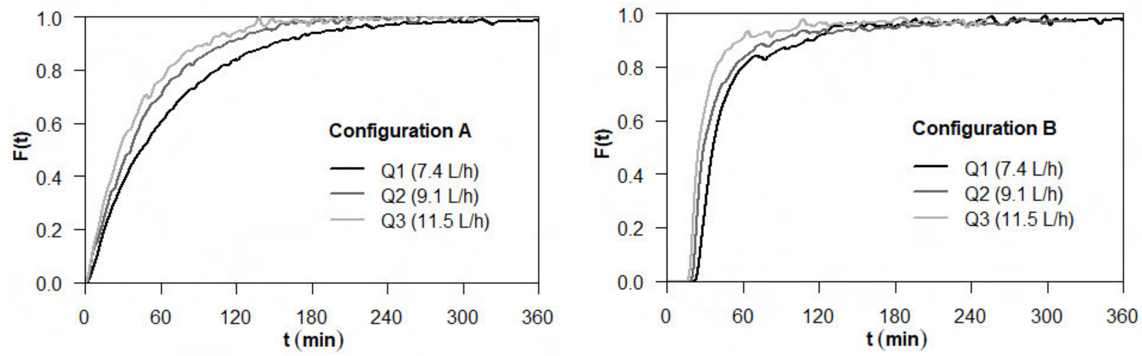
a) b)

Figure 3. Tracer tests at variable water level for circular cross-section tanks for 20% volume variation.

In general, stronger short-circuiting effects occur in the storage tanks operated at variable water levels than in steady-state conditions. Under fill-and-draw mode, the establishment of water pockets of higher residence time is promoted in all tank's configurations, particularly if small water level variation occurs in each cycle. Even when the filling periods are longer than the theoretical mixing time, mixing in the tanks operated with small volume variation in each cycle is far from complete. Consequently, despite results from CFD and tracer small-scale tests at steady-state conditions providing good insights on the hydrodynamics in the tanks, care must be taken when inferring results for full-scale tanks operated at variable water levels.

Rectangular cross-section tanks

A similar analysis was carried out for two configurations (A and B, see Figure 1c) of rectangular cross-section tanks. The cumulative distribution *F(t)* determined for the two configurations A and B with mode 1 and three flow rates is presented in Figure 4. The *F(t)* increases in the beginning of the test in Configuration A (fully open) (Figure 4a), highlighting the existence of short-circuiting phenomena. Configuration B (baffled tank) presents a delayed and sharp increase in *F(t)* at initial times, showing the effect similar to a plug flow regime (Figure 4b). The fact is that baffles prevent the inflowing jet to mix with older water and push older water to the outlet pipe.



a) b)

Figure 4. F(t) for the two configurations at steady-state conditions and for three flow rates: (a) Configuration A; (b) Configuration B.

Short-circuiting and mixing indexes are presented in Table 2 Results are coherent with those obtained for circular cross-section tanks. In rectangular tanks operated with a relatively constant water level, higher flow rates increase the water renewal in open tanks (Configuration A). However, the opposite effect is observed in tanks with interior walls (baffles structures) (Configuration B). When operating the rectangular tanks at variable water levels, the higher the water volume variation in each fill-and-draw cycle, the faster the renewal of stored water becomes, with slightly better results in Configuration B despite the worse mixing conditions. For

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high-volume variations (50% to 80%), the renewal times are very similar in the two configurations; for a 20% volume variation, Configuration B promotes a faster water renewal.

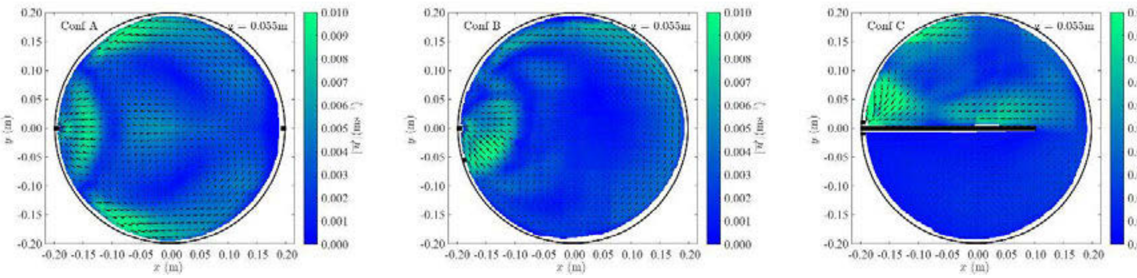
Table 2. Hydraulic indexes for the two rectangular cross-section configurations at steady-state conditions.

Config.	Q (L/h)	τ (min)	t' (min)	t_{10} (min)	t_{95} (min) [1st, last]	$\bar{\sigma}$ (-)	Mo (-)
A	7.4	59.6	61.5	9.6	204	0.86	15.6
	9.1	48.5	49.9	5.7	145	0.92	19.5
	11.5	38.3	38.9	5.4	127	0.70	18.5
B	7.4	59.6	49.1	26.1	130, 180	0.60	4.3
	9.1	48.5	40.5	22.0	175, 183	0.73	4.1
	11.5	38.3	33.7	19.2	103, 238	0.83	3.0

3 SMALL-SCALE TESTING: PIV MEASUREMENTS

Particle image velocimetry (PIV) technology has been used to study flow dynamics in the three configurations of circular-cross section tanks. The experimental facility was adapted to run these tests. A stirring mechanism is installed in the feed tank to mix the PIV seeding particles and to homogenize the inflow water. The experimental PIV system is composed of a laser head and lens, emitting a pulsed laser beam optically transformed into a 2-mm-thick laser sheet, a power supply or laser beam generator, a digital camera, a timing unit and an acquisition and control software. Polyamid Seeding Particles (PSP-50 9080A5011 Dantec Dynamics®, Denmark) with 1.03 of density and a mean particle diameter of 50 μm are used as seeding material in the current tests.

The 2D-PIV can only measure the projection of the velocity into the plane of the light sheet. The PIV system is operated between 0.5 and 15 Hz sample frequency. In each measuring gap, horizontal PIV velocity maps are acquired at three water heights, namely, at 0.010, 0.030 and 0.055 m from the tank bottom. Each plane was composed of the 9 or 12 small sections with 9.5 cm long and 12.5 cm wide. For each acquisition, approximately, 15 minutes of consecutive data are collected. The time-averaged velocity fields, obtained based on instantaneous velocity measurements, are presented in Figure 5 for each tank configuration (A, B and C) and for the horizontal z=0.055 m.



a) b) c)

Figure 5. Time-averaged velocity maps at each configuration and horizontal plane at z=0.055 from the bottom for Configurations a) A, b) B and c) C

The three configurations have very different flow patterns. Configuration A develops two symmetrical vortices in which the water moves onwards along the tank walls and returns in the central zone. Configuration B, given the proximity of the inlet and outlet pipes, enhances the short-circuiting flow path with poor mixing in most of the tank, since part of the incoming fluid is directed to the outlet without mixing with the stored water. Also, the region with lower velocities is located in the central zone of the tank and with higher expression near the tank bottom. In Configuration C, the baffle reduces the short-circuiting and promotes de recirculation and mixing in the first half of the tank, delaying the new water from reaching the outlet pipe.

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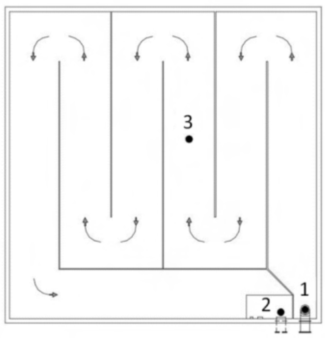
4 FULL-SCALE TESTING

The full-scale tank selected to undertake the tests is an aboveground square cross-section structure made of concrete belonging to Águas do Algarve, the water utility responsible for the water supply and wastewater transport in the South of Portugal. The tank has a capacity of about 3 450 m^3, with an inner side with of 26.6 m, and corridors 5.5 m wide. An inlet pipe, with a 0.8 m diameter, enters the tank near the bottom of the structure, and an elbow with an upward angle directs the flow to the opening at 4.5 m height. The outlet pipe, also with 0.8 m diameter, is located inside a ditch, 1.5 m below the tank floor. This tank features internal baffles that force the flow through a series of 90º and 180º turns between inlet and outlet, and the total length of the water path is approximately 160 m (Figure 6).

Conductivity was monitored at three different locations (Figure 6a): 1) at 1 m inside the inlet pipe; 2) inside the ditch and 1 m below the floor of the tank next to the outlet pipe; and 3) in the middle of the third corridor and 2.8 m from the floor of the tank. Three conductivity probes were installed at each sampling site (two YSI Pro 30 and one YSI 556 MPS) and used to monitor the conductivity and the temperature during the test at 10-minutes intervals.

The test comprised the application of the step tracer method, in which the inflow water with a higher conductivity enters the tank filled with water with lower conductivity. The test started when the intended conductivity was achieved in the WTP (about 3 km from the tank). Inflow and outflow rates respond to the needs of the distribution systems, allowing for a minimum volume variation (ca. 20%). The test lasted until the conductivity between inflowing water and the outflowing differed by less than 5%.



a)

b)

Figure 6. Full-scale tank: a) aerial photo; b) inner view.

Collected data during 6 hours are shown in Figure 7a. During the first six hours, the inflow was practically constant (1 000 ls^{-1}); the outflow varied between 665 and 945 ls^{-1} and the water level varied between 3.6 and 4.5 m, which corresponds to a volume variation of 20%.

The electric conductivity evolution at the three monitoring sites has shown that, even though the water was leaving the WTP with a constant conductivity (ca. 402 μScm^{-1}), it still took approximately 30 minutes for the inflow conductivity to stabilize. Cumulative distribution curves, *F(t)*, show a rapid increase even in the outlet pipe (Figure 7b). Only after 40 minutes it is possible to start noticing the newer water reaching the outlet pipe. After 46 min, the 10% inflow conductivity was reached at the outlet point (t_{10}) and the complete renewal was attained at the intermediate monitoring point (t_{95}); after 1 h 41 min, the water in the tank was completely renewed. Even with the plug flow created by the existing baffle structure, the high flow rates allowed a rapid renewal of the stored water. Some older water pockets come out later and, after 6 hours, the renovation is almost complete. Calculated indexes at the outlet pipe are t_{10}=46, t_{95}=75 and 101 min (first and last) and Mo=1.5

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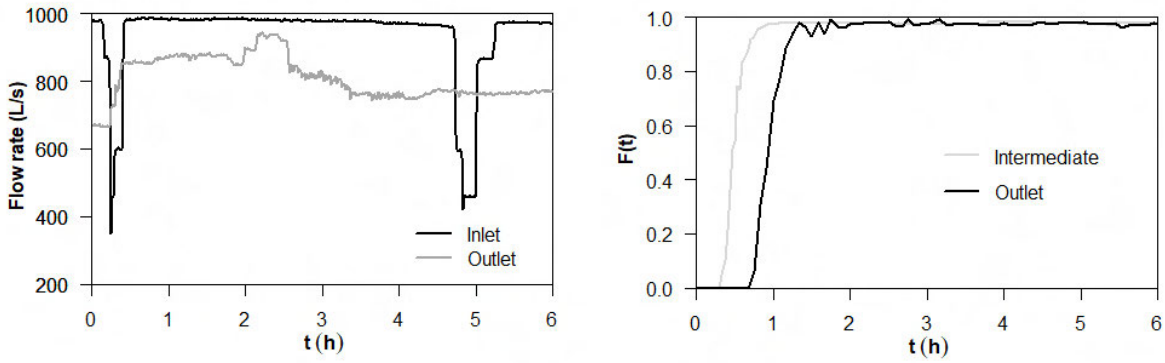

a) b)

Figure 7. Full-scale tests: a) flow rate data; b) cumulative distributions curves.

5 CFD MODELLING

Computational Fluid Dynamics (CFD) modelling has been carried out for a better understanding of the flow hydrodynamics (flow pattern) in circular storage tanks for two inflow configurations: the inlet pipe above the water level (referred to as a plunging jet) and the inlet pipe below the water level (referred as submerged jet).

A 3D CFD model of the small-scale circular cross-section tank of Configuration A was developed using OpenFOAM, a free and high-level language CFD library. The final mesh is refined near the tank walls, inlet and outlet regions and in the air-water interface, which are areas with high-velocity gradients region. The resulting mesh is characterized by 1.4 million mainly hexahedral cells with 1.5 million points of calculus. Less refined meshes settings in the wall were analysed however, the flow pattern obtained by the CFD did not follow the one observed by recorder images of the movement of the dye tracer solution in the laboratory [52]. For the flow pattern analysis, a multiphase solver has been used. For each phase, the solver multiphaseInterFoam captures the interfaces between two (water and air) and includes surface tension and contact angle effects. It uses the finite volume along with the volume of fluid method.

Results for the two configurations are presented in Figure 8 in terms of velocity fields at mid water height. Main differences are related to the direction of the flow paths inside the tank. In a plunging jet, the water enters the tank and sinks downwards; due to the 'Coanda effect' in the tank wall, the water from the jet progresses clung to the tank walls, symmetrically, in the left and right directions, and returns backwards through the tank center. In the submerged jet, the water is directed directly to the outlet pipe and returns backwards along the tank walls.

This research demonstrates that numerical models can capture the 3D behaviour of flow dynamics in water storage tanks. CFD results allow assessing the influence of the nozzle position on the hydrodynamics conditions inside the tank. Each jet generates a preferential flow path or distinct flow pattern and velocity field in the water storage tank. The plunging jet breaks into droplets that fall onto the water surface generating a void responsible for the progression of the jet clung to the tank wall and, then produces a symmetrical flow clung to the walls and a flow in the centre of the tank. The submerged jet generates a long entrainment path with high velocities through the center of the tank, promoting an enhanced water mixture by the turbulence created and a flow towards the inlet along the walls.

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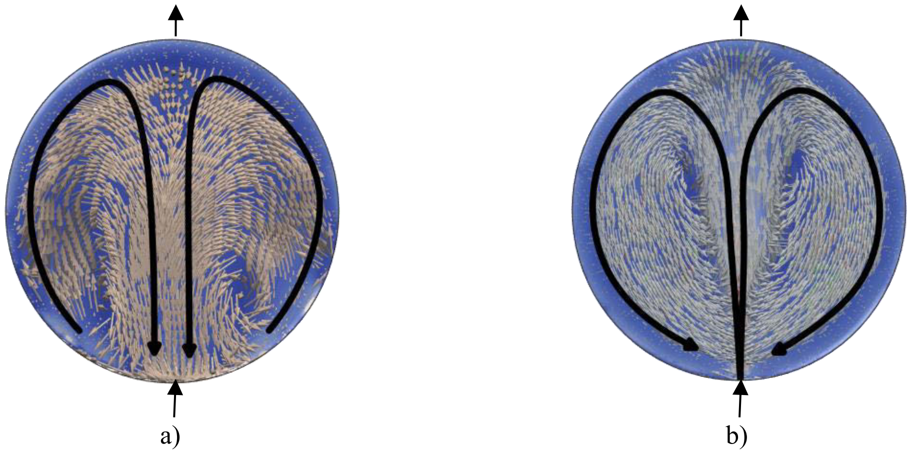

Figure 8. CFD results at mid water height for circular tanks: a) plunging jet and b) submerged jet.

6 MIXING IMPROVEMENT MEASURES

The effect of different types of measures on water mixing in circular and rectangular cross-section tanks is investigated. Several structural improvement measures are analysed: i) the inlet pipe diameter effect (two diameters were tested, 2 and 4 mm, in the circular cross-section tank); ii) the use of multiple nozzles effect (three nozzles were tested in circular cross-section tank and 10 nozzle configurations in rectangular cross-section tanks); iii) the effect of baffles with different lengths (0%, 50% and 75% of the diameter of the circular cross-section tank); iv) the use of baffles with holes (in rectangular cross-section tanks); and v) one operational improvement measure which corresponds to operating the tank with variable water level, that is with fill-and-draw cycles with several amplitudes of the volume variation (20%, 50% and 80%) in the circular cross-section tanks (Configurations A, B and C).

Tracer tests with NaCl have been carried out for a more qualitative analysis and dye tracer tests for a more qualitative analysis. Figure 9 shows examples of dye tracer tests carried out in the rectangular tanks of configuration A with different number, orientation and location of nozzles (referred as S2, S3, S5, S6 and S7). Different flow paths are established depending on the location and orientation of the nozzles within the tank.

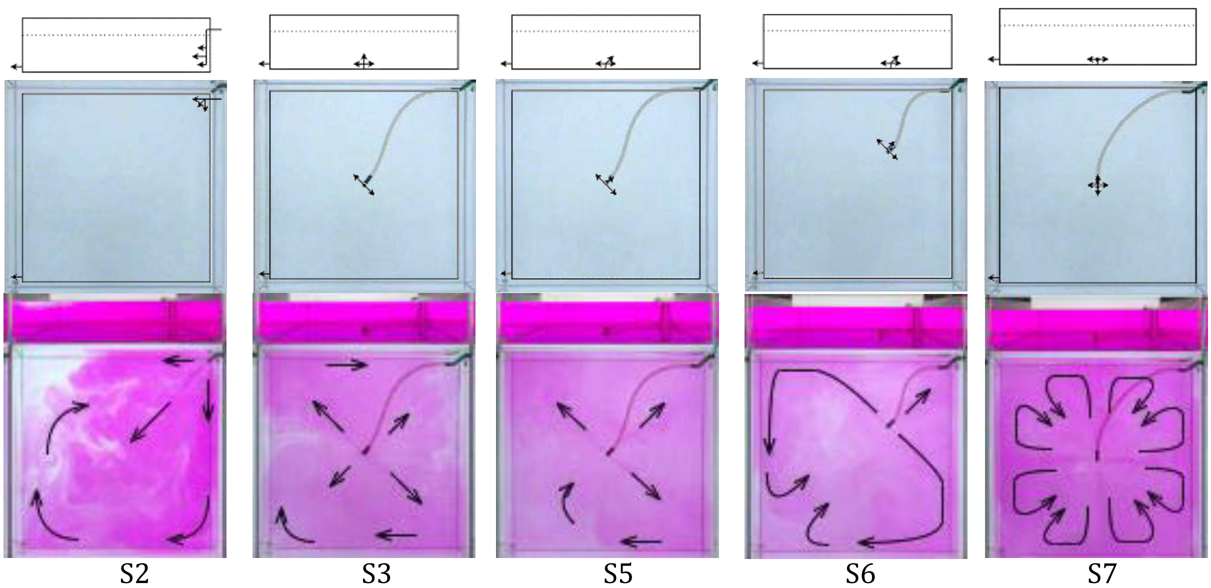

Figure 9. Rectangular tank configuration A: dye tracer tests for several locations and orientations of nozzles.

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The hydraulic indexes calculated for the circular cross-section tank for constnat water level and for the flow rate Q3 are shown in Table 3. Similar conclusions can be drawn from the tests in retangular cross-section tanks.

Table 3. Hydraulic indexes for the circular cross-section tanks for constant water level and for Q3.

Configu-ration	**Improvement measure**	**Inlet pipe** (mm)	**Morrill index** *Mo*	**Short-circuiting index**		**Turnover time**	
				θ_{10}	Variation	θ_{95}	Variation
Circular A	Initial conditions	4	12	0.19		3.10	
	Inlet diameter reduct.	2	23 🟢	0.11	– 39 % 🔴	3.67	+ 15 % 🔴
	Nozzles	6 × 1	18 🟡	0.13	– 30 % 🔴	3.18	0 % 🟡
		4 × 1	20 🟢	0.12	– 36 % 🔴	3.36	+ 6 % 🔴
		6 × 1	22 🟢	0.10	– 44 % 🔴	3.10	– 2 % 🟢
Circular B	Initial conditions	4	46	0.06		4.78	
	Inlet diameter reduct.	2	18 🟢	0.13	+ 117 % 🟢	3.13	– 34 % 🟢
	Nozzles	5 × 1	15 🟢	0.17	+ 183 % 🟢	3.27	– 32 % 🟢
		7 × 1	19 🟢	0.14	+ 133 % 🟢	3.32	– 31 % 🟢
		3 × 1	26 🟢	0.10	+ 67 % 🟢	3.12	– 35 % 🟢
	Baffle 50%	4	9 🔴	0.26	+ 550 % 🟢	2.87	– 31 % 🟢
	Baffle 75%	4	7 🔴	0.32	+ 433 % 🟢	2.76	– 42 % 🟢
Circular C	Initial conditions	4	7	0.32		2.76	
	Inlet diameter reduct.	2	11 🟢	0.21	– 33 % 🔴	3.35	+ 21 % 🔴

Note: 🟢 positive effect; 🟡 identical effect; 🔴 negative effect

Operating the tanks with fill-and-draw cycles, with large water volume variation, globally improves the water mixing conditions, reduces the short-circuiting effect and reduces the renewal time for all circular cross-section tanks and for rectangular tanks without baffles. The higher the water volume variation is, the most effective this measure becomes on improving mixing and renewal conditions. Still, this measure increases slightly the short-circuiting in rectangular tanks with baffles. Operating the tanks with fill-and-draw cycles is, indeed, the simplest and the most cost-effective water mixing and renewal measure. The only disadvantage is that operating the tank with not-full storage reduces the supply system reliability in case an abnormal situation occurs at upstream the tanks that interrupts the supply during several hours.

Both the reduction of the inlet pipe diameter and the use of multiple nozzles near the tank bottom far from the inlet pipe are the most efficient structural measures to improve mixing; though the short-circuiting effect can increase in circular tanks configurations A and C. Tests in circular cross section tanks have shown that the nozzles should be more than three directed to the horizontal or making a 45º angle with the horizontal. Tests in rectangular tanks carried out for 10 different nozzles locations, sizes and number have shown that: the most efficient solutions those with nozzles near the tank inlet at different water depths and pointing to the tank lateral wall, or nozzles (≥4) in the tank centre with horizontal or 45º angle jets. Few nozzles located in the centre of the tank with vertical jets should be avoided.

The use of baffles promotes the plug-flow and, consequently, worsens the water mixing conditions; however, baffles reduce the short-circuiting effect and reduce the renewal time. These structures are very important in tanks of water transmission systems, namely at downstream water treatment works or at intermediate locations in the system, far from distribution networks; that is in tanks in locations in which the water passes and stays very few time. Conversely, in tanks located immediately at upstream distribution systems, with large volumes, with high retention times and with tendency to have lower disinfectant concentrations, it is recommendable to increase inlet water momentum by reducing the inlet pipe diameter and by using nozzles.

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The use of smaller-size baffles (i.e., 50% of the diameter, instead of 75%) is more efficient for improving mixing conditions in tanks with close inlet/outlet pipes. The use of small holes in baffle structures (as tested in rectangular tanks) have shown hardly any effect, which may have been due to the small-size of the tested holes (1-2 mm). Further research is necessary to assess the effectiveness of this measure.

7 CONCLUSIONS AND FUTURE WORK

The main findings of this research are that the most effective operational measure is operating tanks with fill-and-draw cycles, however, when the tank is operated nearly full to assure the maximum reliability of the system, structural measures are recommendable. Reducing the inlet pipe diameter and installing nozzles near the tank bottom improve the mixing conditions being advisable in large storage tanks located upstream distribution network to maintain disinfectant concentration levels. The use of baffles is recommendable in large tanks located at intermediate locations of the transmission system and with the inlet and outlet pipe located very close.

In terms of future work, other tank configurations (e.g., inlet and outlet pipe locations; different inlet nozzles configurations; with other H/D ratio) and operating conditions (e.g., different demand profiles) should be tested. PIV tests should be carried out for vertical planes for studying the 3D nature of the flow and for different inlet pipe configurations (e.g., for the submerged jet and for different nozzles). CFD simulations should be extended to find the optimal design of nozzles in terms of their location (above the water surface, near the tank bottom, or elsewhere), the ideal number of nozzles and the direction of the water jets.

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