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Aqualibrium competition: laboratory data and EPAnet simulations

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Abstract

The Aqualibrium competition [1] is a fun way to learn about water supply and distribution. A pipe network has to be built with the aim of equally distributing a given volume of water between three reservoirs. The rules of such a competition prescribe that a looped network has to be built and this makes the problem quite complex because of the well-known non-linearity of the governing equations. EPAnet is a powerful tool to improve and fasten the solution of the problem. At the Water Engineering Laboratory (WEL) of the University of Perugia an Aqualibrium equipment is used within the Civil Engineering courses. EPAnet was used to simulate the behaviour of the Aqualibrium network, but the results showed some discrepancies between laboratory tests and numerical simulations under some flow conditions. These discrepancies, as well as the critical role played by energy dissipation mechanism, are discussed in this paper.

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Keywords: EPAnet; Aqualibrium competition; local head loss; pipe systems

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1. Introduction

The Aqualibrium competition is a fun way to learn about the difficult work of designing and verifying water supply and distribution pressurised pipe systems. The aim of the Aqualibrium competition is to distribute three liters

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of water equally between three reservoirs (containers). Participants build a pipe network between a water source and the three reservoirs by using pipes of different diameters. While the competition is simple to understand and fun to do, the underlying problem is highly complex: the three small reservoirs can be placed in more than 3000 combinations, and potentially there are 280 billion possible pipe networks for each one of these combinations.

In this paper, EPAnet [2] is used to simulate the behaviour of some Aqualibrium networks: the location of the three reservoirs is fixed "a priori", and the pipe network is designed by the groups of students participating in the competition. Then two types of checks are executed: i) using EPAnet, and ii) in the laboratory. Discrepancies between laboratory tests and numerical simulations are discussed by pointing out the possible causes.

2. Aqualibrium competition: equipment, rules, and simulation by EPAnet

2.1. Equipment and rules of the Aqualibrium competition

The goal of the Aqualibrium competition [1] is to distribute a given volume (= 3 L) equally between three reservoirs located in three nodes on a grid of 16 nodes using a network of pipes (Fig. 1). In the networks considered in this paper the reservoirs are placed at nodes 7, 14, and 16 of the grid (in the following, R1 indicates the reservoir connected to the grid node 7, R2 to 14, and R3 to 16, respectively). Such reservoirs are connected to the network by means of three outlets discharging into the atmosphere (rp1, rp2, and rp3, respectively). The competition sheet is placed on a horizontal table and all elevations are referred to it. The source container (in the following SC) is hung from the source stand and the main supply pipe is connected to its base. The main supply pipe is connected at node 1 of the competition sheet by a shut-off valve. The participants design a pipe network by using: (i) plastic pipes of a length, L, equal to 0.28 m and internal diameter, D, equal to 3 mm or 6 mm, and (ii) connectors of a different shape: straight connector, 90° bend, T or cross junction. Pipes must align with the grid on the competition sheet, and where two or more pipes meet at a junction they must all be connected to each other. No more than 8 lines on the competition sheet's grid may be left without a pipe: this implies that there must be at least one closed loop in any network. Before the test is executed air must be removed from the system. Once the air is completely removed, the shut-off valve is closed. To prepare for the final run, the reservoirs are emptied while leaving the network pipes full of water. At the beginning of the test, the shut-off valve is opened fully: when 3 L of water have been supplied, the run is stopped by closing the shut-off valve. The volume in each reservoir, W_i, is measured by means of a measuring cylinder. The performance of the designed network, i.e. whether or not the supplied 3 L are distributed equally between the three reservoirs, is measured by means of the relative total penalty index, P:

$$P = \frac{\sum_{i=1}^{3}\left|W_i - 1L\right|}{1L}100 \tag{1}$$

where the numerator is the sum of the absolute difference between the actual volume of water in the i reservoir, W_i, and the due volume (i.e., 1 L). The group who designed the network with the smallest value of P wins the competition.

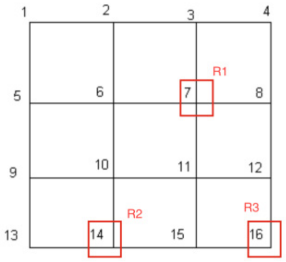


Fig. 1. Aqualibrium competition: the sheet with the location of reservoirs chosen for the Perugia tests.

2.2. Simulation of the Aqualibrium competition by EPAnet

Since the network is not an open tree type, the solution is not obvious and a simulation by means of a hydraulic network package such as EPAnet is required. EPAnet is a public domain water distribution system modeling software package developed by the United States Environmental Protection Agency [3]. It performs extended-period simulations of hydraulic and water-quality behavior of pressurized pipe networks. The underline hydraulic problem is solved by means of the Global Gradient Algorithm [4,5]. To build an Aqualibrium network in the software, the following boundary conditions are imposed: (i) the source container SC is simulated by a tank in which the initial head is equal to 0.88 m, and (ii) a constant head, equal to their elevation (= 0.12 m), is assumed at the three reservoirs. Since for real pipe systems the duration of a scenario is of the order of some hours, the standard version of EPAnet assumes 1 minute as the minimum time step in an extended period simulation. Such a feature does not allow a proper simulation of the dynamics of the executed tests, which last about 2 minutes. As a consequence, a procedure has been used in which, for any time step (equal to 10 s) and given head at the source container, the supplied discharge allows evaluating the head in the successive time step on the basis of the continuity equation at SC.

During the simulations two phases can be distinguished: phase 1) when pipes are considered as long by neglecting all local head losses (e.g., at junctions, cross-section changes, and bends), and phase 2) when local head losses are taken into account by associating the local head loss coefficient to the pipe located downstream of the local head loss. The aim of phase 1 is to guide the building of the network and assess the flow distribution in correspondence to junctions (as discussed below, this is essential for evaluating properly the corresponding local head losses). The aim of phase 2 is to refine the analysis of energy dissipation by considering both friction and local head losses. In EPAnet the friction losses, ΔH, are calculated using the Darcy-Weisbach formula:

$$\Delta H = \frac{fV^2L}{2gD} \tag{2}$$

where g = acceleration due to gravity, V = mean flow velocity, and the friction factor, f, is given by a different formula according to the flow regime. In particular, the Hagen–Poiseuille formula is used for laminar flow (when the Reynolds number, $Re = VD/\nu$, is smaller than 2000, with ν = kinematic viscosity). A cubic interpolation from the Moody Diagram is used for the critical zone ($2000 < Re < 4000$) [6], and the Swamee and Jain approximation to the Colebrook-White equation is used for turbulent flow ($Re > 4000$) [7]. The roughness of the plastic pipes is assumed equal to 10^{-5} mm. The local head loss, ζ, at a singularity is evaluated by means of the Borda equation:

$$\zeta = \chi \frac{V_d^2}{2g} \tag{3}$$

where χ = local head loss coefficient, and the subscript d indicates the pipe downstream of the singularity. In Tab. 1, the values of χ are reported for the singularities of the Aqualibrium networks where the local head loss coefficient depends only on its geometrical characteristics (A = pipe cross section, and the subscript u indicates the pipe upstream of the singularity). On the contrary, for T or cross junctions (hereafter referred to as junctions) χ depends not only on the geometrical characteristics but also on the flow distribution, which is an unknown of the problem. Consequently, a trial and error procedure has been followed within phase 2. Precisely, when pipes are considered as short, the first value of χ at junctions is evaluated by considering the flow distribution obtained from phase 1 (long pipes). Then, the resulting values of the flow velocities are compared to the ones given at the previous step; if the error, ε, defined as:

$$\varepsilon = \frac{\left(V_{n^{th}phase} - V_{n-1^{th}phase}\right)}{V_{n^{th}phase}} 100 \tag{4}$$

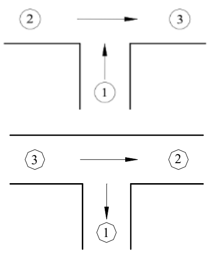
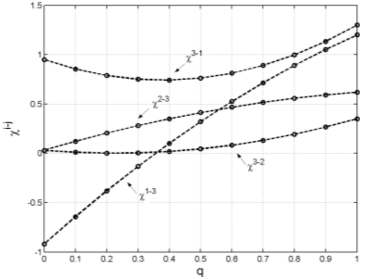
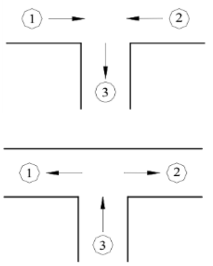
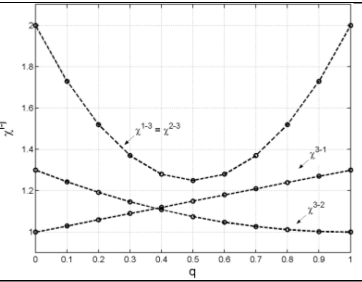
is small, the procedure stops, otherwise it is reiterated by considering the new flow distribution.

As discussed in [8], the mechanism of the energy exchange at a junction between one stream to another can lead to negative values of χ. However, as expected, an energy dissipation occurs at a junction as a whole. Moreover, it is worthy of noting that literature is not exhaustive about energy dissipations occurring at junctions even if they are frequently used in both water and fire flow distribution systems [9]. For example, in Tab. 2 the local head loss coefficient $\chi^{i\text{-}j}$ for four types of T junctions are given, with i-j and Q indicating the flow path and the flow discharge, respectively. For all types of these junctions, pipe 3 is the combined flow leg and for each path the local head loss is evaluated by assuming $V_d = V_3$ in Eq. (2).

Table 1. Local head loss coefficients for the "geometrical" singularities in the Aqualibrium networks.

Singularity type	local head loss coefficient, χ
square-edged inlet	0.5
completely open shut-off valve	0
sudden enlargement	$(A_d/A_u\text{-}1)^2$
sudden contraction	$0.5(1\text{-}A_d/A_u)$
90° bend with a curvature radius r = 0.02 m	$0.21/\sqrt{(r/D)}$
180° bend with a curvature radius r = 0.02 m	$1.4[0.21/\sqrt{(r/D)}]$

Table 2. Local head loss coefficients for T junctions (modified by [8]).

T junction type	local head loss coefficient, χ, vs. $q=Q_1/Q_3$
	
	

Compared to T junctions, literature offers much less insight into the behavior of cross junctions. For combing flow cross junctions, the Levin formula can be used, whereas for the other types of cross junctions an approximate approach is suggested: to simulate them as T junctions by deleting the branch with the smallest discharge/diameter [10]. More recent contributions can be found [9], where experiments are carried out for several types of cross junctions, but in a limited range of velocity (0.3 m/s < V < 4 m/s). In the writers' opinion, Computational Fluid Dynamics seems to be a promising approach for evaluating energy dissipation at cross junctions [11].

In this paper the relationships reported in [8], [9], and [10] were used to evaluate the local head loss at T and cross junctions.

3. Three examples of the Aqualibrium networks

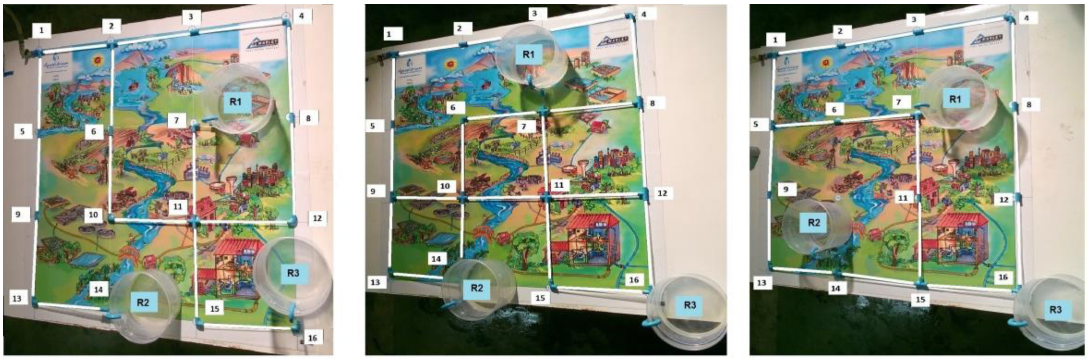
In this paper three networks – distributing water to reservoirs R1, R2, and R3 – are considered since they are representative of all the designed networks. All these systems strictly follow the rules of the Aqualibrium competition.

3.1. Laboratory tests

In Fig. 2 a photo of the selected networks is shown. Moreover in Tab. 3 the number of T, N_T, and cross junctions, N_X, along with the experimental values of W_i and P are given. With regards to the geometrical characteristics of the network it can be noted that network #1 is characterized by the smallest number of junctions, whereas network #2 has the largest value of N_T and N_X. The experimental check of the designed pipe systems shows that networks #1 and #2 allow distributing the given volume almost equally between R1, R2, and R3, with a very small relative total penalty index, P (Fig. 3). On the contrary, a larger value of P is observed for network #3 (= 25.2%), in which it is difficult to remove air in the part of the system connecting nodes 7, 14, and 16 (Fig. 2c), where the flow seems to be practically equal to zero (see also the below discussion). This hinders the repeatability of the experiments.

Table 3. Geometrical characteristics and experimental performance of the networks.

Network #	N_T	N_X	W_1 (L)	W_2 (L)	W_3 (L)	P (%)
1	2	1	0.983	0.975	1.042	8.4
2	6	3	1.050	0.993	0.957	10.0
3	6	0	0.954	0.920	1.126	25.2



a) Network #1 b) Network #2 c) Network #3

Fig. 2. The three examined networks on the Aqualibrium competition sheet at the University of Perugia.

3.2. EPAnet simulation

In Fig. 4 a diagram of the three networks at the first time step of phase 1 of the numerical simulation by EPAnet (long pipes) is reported: the color indicates the flow regime (laminar flow in red, critical zone in blue, and turbulent transition zone in green; pipes with laminar flow with Re<200 are indicated by a dashed line), whereas the line thickness indicates the pipe diameter, with the largest one corresponding to 6 mm diameter (and the smallest to 3 mm).

From Fig. 4 it can be observed that pipe 1 in networks #1 and #2 is in turbulent transition zone (because of the very small value of the roughness the actual flow regime is smooth turbulent flow), whereas in network #3 a critical flow regime takes place. In network #1 laminar flow happens in few and dispersed pipes, whereas in networks #2 and #3 the laminar flow concerns a large part of the system. Moreover, it is often highly laminar flow, i.e., some pipes are characterized by a very small Reynolds number (network #2: pipe 10: $Re = 100$, pipe 12: $Re = 105$, pipe 15: $Re = 24$, pipe 19: $Re = 154$, pipe 7: $Re = 199$; network #3: pipes 10, 13: $Re = 2$, pipe 16: $Re = 10$, pipe 17: $Re = 8$).

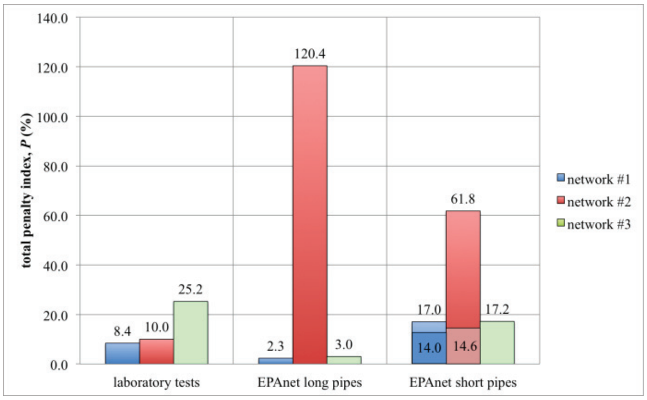


Fig. 3. Total penalty index for laboratory tests and numerical simulations.

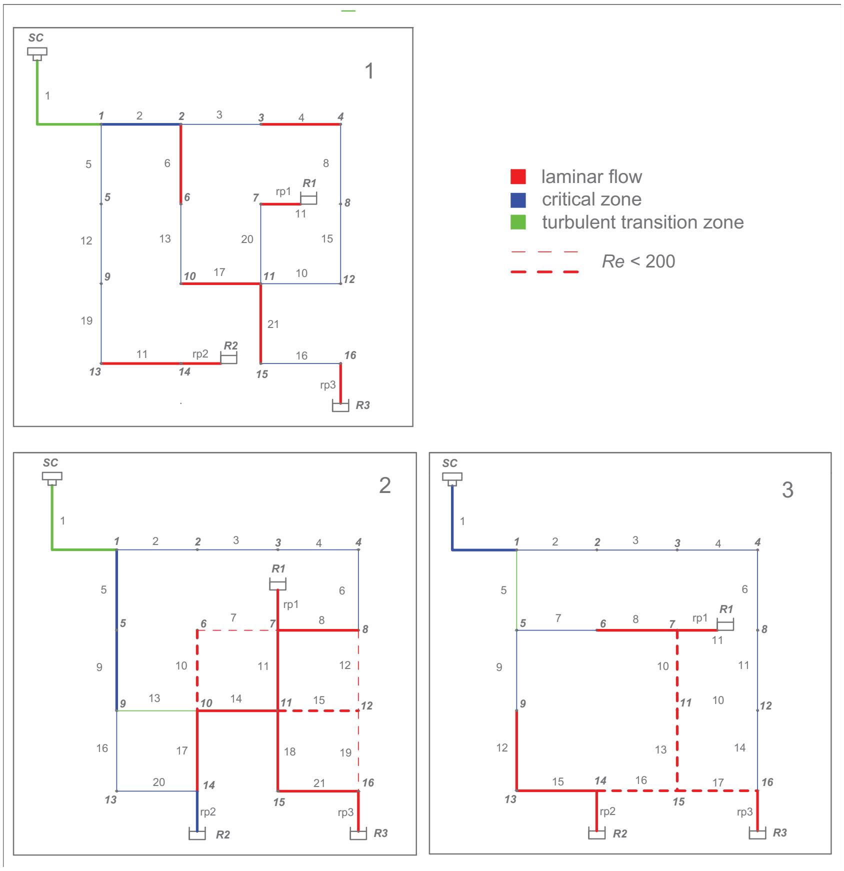


Fig. 4. The three examined networks: diameter and initial flow regime distribution at the first time step of phase 1 (thin lines $D = 3$ mm; thick lines $D = 6$ mm; pipes with the very low Reynolds number are indicated by dashed lines).

From Fig. 3 clear differences emerge between the values of P from the laboratory and those given by EPAnet, with the largest difference happening in network #2 (P = 10.0% in the lab and P = 120.4% in the EPAnet simulation). As expected, the results of the simulation improve when local head losses are taken into account, and the resulting value of P is closer to the laboratory one.

As mentioned above, an iterative procedure has been followed within phase 2; as an example, in Tab. 4 the results for network #1 are given, by considering the initial value of the head at the source container SC. Because of the presence of three junctions (the T junctions at nodes 1 and 2 and cross junction at node 11), the velocities obtained in phase 1 are initially used to evaluate the corresponding χ. With these values of χ, the velocities of the first iteration of phase 2 are derived by using the contour plots given in [9], with a maximum error ε = 15% with respect to the previous ones. In order to reduce such an error, and consequently evaluate better χ of junctions 1, 2 and 11, the procedure is reiterated once: the resulting values of the velocity differ very little from the previous ones ($\varepsilon \leq 0.20\%$).

The role of the local head losses is very evident in the simulation of network #2, with a result of a better agreement with the laboratory data. In fact, the penalty index, which is equal to 10.0 % in the lab and 120.4% when long pipes are considered, decreases significantly with the value depending on the formula used for evaluating cross junction local head losses: 61.8% or 14.6% for the [9] and [10] formulation, respectively. It is worth noting that, in most of pipes of network #2, flow conditions are outside the range of the experiments executed in [9].

For the sake of completeness it has to be pointed out that for networks #2 and #3 the number of the iterations increases. Moreover, the trial and error procedure followed for evaluating junction head losses does not converge for network #3 since in pipes with the very low Reynolds number – indicated by dashed lines in Fig. 4 – during the procedure the direction of flow changes repetitively. According to Tab. 2, this causes a change in junction type, and then in the formula to be used.

Table 4. Network #1: trial and error procedure at the first time step.

Link ID	L (m)	D (mm)	phase 1 (long pipes)		phase 2 (short pipes) – 1st iteration				phase 2 (short pipes) – 2nd iteration			
			V (m/s)	Re	χ	V (m/s)	Re	ε (%)	χ	V (m/s)	Re	ε (%)
Pipe 1	1.1	6	0.779	4676	1.41	0.711	4265	-8.79%	1.41	0.711	4263	-0.03%
Pipe 2	0.28	6	0.518	3106	2.59	0.455	2732	-12.05%	2.59	0.455	2730	-0.05%
Pipe 3	0.28	3	0.776	2328		0.682	2046	-12.11%		0.681	2042	-0.20%
Pipe 4	0.28	6	0.194	1164	9.00	0.170	1023	-12.11%	9.00	0.170	1021	-0.20%
Pipe 5	0.28	3	1.046	3139		1.022	3066	-2.33%		1.022	3066	0.00%
Pipe 6	0.28	6	0.324	1942		0.285	1709	-12.01%		0.285	1710	0.04%
Pipe 8	0.28	3	0.776	2328	0.46	0.682	2046	-12.11%	0.46	0.681	2042	-0.20%
Pipe 10	0.28	3	0.776	2328	-0.22	0.682	2046	-2.33%	-0.22	0.681	2042	0.00%
Pipe 11	0.28	6	0.262	1570	9.12	0.256	1533	-12.01%	9.12	0.256	1533	0.04%
Pipe 12	0.28	3	1.046	3139		1.022	3066	-12.11%		1.022	3066	-0.20%
Pipe 13	0.28	3	1.295	3884	0.38	1.139	3418	-12.01%	0.38	1.140	3419	0.04%
Pipe 15	0.28	3	0.776	2328		0.682	2046	-2.33%		0.681	2042	0.00%
Pipe 16	0.28	3	1.029	3086	0.46	0.935	2805	-9.10%	0.46	0.935	2804	-0.05%
Pipe 17	0.28	6	0.324	1942	9.12	0.285	1709	-14.96%	9.12	0.285	1710	-0.05%
Pipe 19	0.28	3	1.046	3139		1.022	3066	-12.11%		1.022	3066	-0.20%
Pipe 20	0.28	3	1.042	3126	1.25	0.886	2658	-2.33%	1.25	0.886	2657	0.00%
Pipe 21	0.28	6	0.257	1543	1.50	0.234	1403	-2.33%	1.50	0.234	1402	0.00%
rp1	0.16	6	0.260	1563	9.39	0.222	1329	-9.10%	9.39	0.221	1328	-0.05%
rp2	0.16	6	0.262	1570	0.28	0.256	1533	-9.10%	0.28	0.256	1533	-0.05%
rp3	0.16	6	0.257	1543	9.39	0.234	1403	-14.96%	9.39	0.234	1402	-0.05%

4. Conclusions

Notwithstanding the small number of the considered cases, the above analysis of the behaviour of three pipe networks within the Aqualibrium competition offers some interesting elements to be discussed. In particular, the discrepancies between laboratory and numerical simulations by means of EPAnet are worth investigating.

The possible reasons of the shown differences may concern two important aspects: i) the evaluation of local head losses, and ii) the effects of the errors in the extended period simulation approach.

The results of the EPAnet simulation when pipes are considered as short – i.e. when minor head losses can not be neglected – show the important role played by the formula used to simualte energy dissipation, with particular regard to junctions where the minor losses depend not only on the geometrical characteristics but also on the flow distribution. As discussed above, even though junctions are common features of pipe systems, literature does not cover a wide enough range of flow conditions. Particularly, the case of very small Reynolds number conditions merits further in-depth analyses. It is worth noting that this issue has not only a theorethical interest but it may also be important to simulate more properly the behavior of real systems (for instance, when a severe failure event occurs or water quality is simulated under low flow conditions). Moreover, a more reliable simulation could be obtained by assuming a different χ value for each time step of the exended period simulation according to the actual flow distribution [12].

Finally, it has to be pointed out that inertial effects are neglected in the extended period simulations; nevertheless, a transient event is generated by fully opening the shut-off valve. Even if this transient is mitigated by the fact that the system is already under some pressure, the total duration (100-150 s) of the test is comparable with the transient's run time, and it could influence the test, especially during the initial part of the run.

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