DRY FOUNTAINS OF UPB: OPERATION MODELLING AND POWER CONSUMPTION ASSESSMENT

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The paper focuses on the dry fountains (pedestrian type fountains) recently commissioned in the campus of the University POLITEHNICA of Bucharest (UPB), consisting of 12 water jets in a straight line. Each water jet rises from an A-type nozzle installed just below the pedestrian level, upon a water flow pattern that is individually controlled by an adjustable fountain pump. LED spotlights are installed into the pavement for each nozzle. An intelligent control system drives the fountains, to produce a water show, based on dancing jets and different light colours. The operation of Dry Fountains of UPB was modelled using GNU Octave and AutoCAD software, to mimic the dancing jets. The proposed theoretical approach allows computing the electric energy consumption of the fountains, for a water show full sequence derived from video recordings, based on hydraulic and mechanical parameters attached to the numerical model that mimics the real hydraulic system.

Keywords: dancing jet, dry fountain, variable speed driven pump, water show

1. Introduction

Water fountains are eye-catching, so they enhance the urban landscape [1]. World's most famous public water fountains are ranked from two perspectives:

- architectural viewpoint, with emphasis on aesthetics – e.g. *Fontana di Trevi*, inaugurated in 1762, which is not only the most beautiful fountain in Rome, but one among the 10 world's most beautiful and heart touching fountains;
- spectacular water show viewpoint, relying on cutting-edge technology, allowing to produce amazing water effects synchronized with music and colourful lights – e.g. the *Fountains of Bellagio*, inaugurated in 1998, which

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are not only the most iconic in Las Vegas, but also the most well-known choreographed fountains in the world, being ranked as the world's largest performing fountains (Guinness World Record in 1999), until 2020.

Fountains of Bellagio features and performances [2] inspired the design of many "dancing fountains" commissioned worldwide, ranked as urban landmarks. Most of the outdoor water fountains are only decorative, while few are interactive too [3], like the so-called "dry fountains", which are viewed as a subsequent type of dancing fountains. Dry fountains (also called "pedestrian type fountains") have the water pool, hydraulic circuit and all equipment hidden underground; water is pumped and individual jets rise from nozzles installed just beneath the pavement.

The present paper focuses on the operation of dry fountains. The aim of the study is to provide a theoretical approach that allows computing the electric energy consumption of the selected facility (dry fountains), based on geometric, hydraulic and mechanical parameters attached to the numerical model of the facility. Since the operation of such fountains involves producing dancing jets, a water show sequence must be considered. The appropriate pumping algorithm ensures the requested water flow pattern, thus the jet heights time-patterns. When modelling dry fountains, the first challenge is to build the numerical model of the hydraulic circuit, where the most important components are the nozzles, which introduce minor hydraulic losses. The second challenge is to set the correct pump scheduling algorithm, namely the start/stop and variable speed time-pattern of each pump, to deliver the flow rates and pressures requested to produce the jets.

The present study points on the recently commissioned dry fountains, installed in the campus of the University POLITEHNICA of Bucharest (UPB). Details on the hydraulic system are provided in Section 2. *Dry Fountains of UPB* operation was modelled using specialized software (namely, GNU Octave [4-5] and AutoCAD [6]), to mimic the dancing water jets. The numerical model and theoretical approach are described in Section 3, while results and discussions are presented in Section 4.

2. Dry Fountains of UPB: System description

The *Dry Fountains of UPB* were built in 2019 in the university campus, in front of the main entrance of *UPB's Aula* (Fig. 1). They consist of 12 water jets, aligned on a single straight line, where each jet rises from a nozzle installed just below the ground level (pavement). Each water jet pattern is controlled separately by a variable speed driven pump – there are 12 such fountain pumps. Various water effects, like pop-up, wave or splash effects, are produced by the above controllable pumps and special nozzles. LED spotlights are installed into the pavement for each nozzle. An intelligent control system drives the fountains, to produce a water show with colourful dancing jets (where the lighting effects are individually set per jet). The *Dry Fountains of UPB* were built by a Romanian company [7], mainly based on fountain technology and equipment provided by a well-known German company [8], which developed and completed several public fountains projects in Romania [9, *Projects/ Public Areas*], starting in 2012 with 3 different types of fountains for 3 major cities (Deva, Arad and Timișoara) in the Western part of the country, and culminating in 2018 with the impressive choreographed fountains in Bucharest, known as "*Unirii Square*" *Fountains* [8, *Entertainment Fountain/ Public area – Bucharest*].

(a)  (b) 

Fig. 1. *Dry Fountains of UPB*, in front of *UPB's Aula* (a) & rising jet (b) – photos from July 2021

For the present case study, the available documents and data attached to *Dry Fountains of UPB* were limited to the main equipment operating/technical instructions and basic measurements related to the geometry of the accessible part of the fountains. Missing data related to the underground water pool and distribution network geometry were estimated based on builder's data evidence [7]. Personal observations, as well as many photos and video recordings were used to perform the hydraulic analysis of the fountains operation. Therefore, the hydraulic system described in this paper can be viewed as the best match of the existing hydraulic system (the best equivalent system).

The main components of the studied dry fountains with 12 jets are:

- a narrow underground pool, filled with about $9.5\,\mathrm{m}^3$ of fresh water – due to the lack of space, the pool capacity is much smaller than recommended [10], but a synthetic rubber (EPDM rubber) waterproofing membrane allows catching the water that falls around the pool on a total surface of about $50\,\mathrm{m}^2$ ($2\,\mathrm{m}$ around each nozzle), returning it into the pool;
- 12 controllable submersible fountain pumps – model *Varionaut 150/DMX/02* [8, *Water Movement/ Controllable Pumps*], with horizontal axis, mounted inside the

pool, on a horizontal metallic frame (Fig. 2); the pumps are labelled from P1 to P12, where pump P1 is the nearest to *UPB's Aula* building;

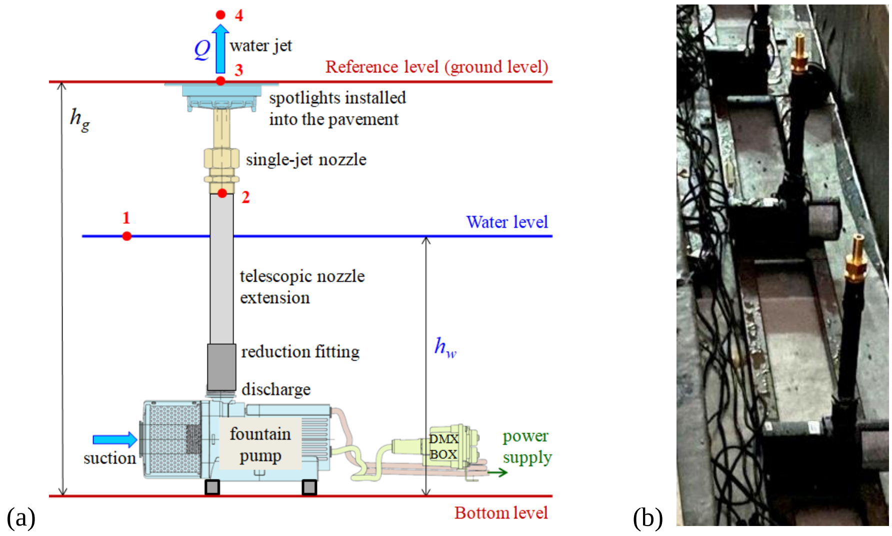

Fig. 2. Water jet feeding system scheme (a) and photo taken during the fountains execution (b): water depth h_w, gap depth h_g and characteristic points 1÷4 (point 4 is at the upper part of the jet)

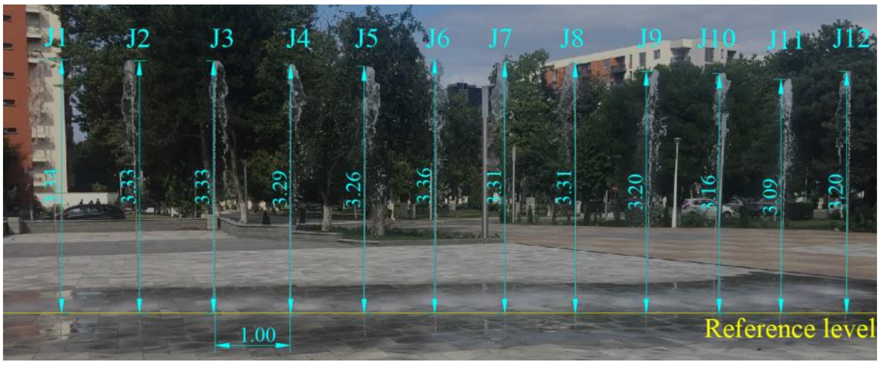

Fig. 3. Rising jets J1÷J12: each jet height h is measured in metres with respect to the Reference level (ground level); distance between two consecutive jets axes is 1.00 m (horizontal arrow)

• 12 single-jet nozzles of A-type – model *Comet 10-12 Silver* [8, *Effect Creation/ Water Effects/ Comet Silver*], vertically placed just below the ground level; the discharge of each pump is connected through a reducing sleeve to a telescopic nozzle extension, which is upper screwed onto the A-type nozzle, as in Fig. 2;

• 12 waterproof spotlights installed into pavement (fig. 1b) – model *ProfiPlane LED L RGB Spot DMX/02* [8, *Illumination*], each with a central opening to accommodate the nozzle below (fig. 2a); the rising jets are labelled from J1 to J12 as in fig. 3, in accordance to their corresponding pump (P1÷P12); the distance between two consecutive jets axes is 1m, yielding a total length of 11m of the orifices alignment line, along which the jets rise;

- water recirculation and filtration system, with centrifugal pump – model *FIJI 6*, operating at a duty point of 5 m pumping head and 6 m^3/h discharge [11], and sand-filter – model *Gre FS400*, of 6 m^3/h flow rate [12];
- dosing pump and control devices for the automatic chemical water treatment;
- submersible drainage pump – model *Calpeda GM10*, covering the operation range of $2.2 \div 7.5$ m pumping head and $3 \div 12$ m^3/h discharge [13];
- system for the remote control, diagnosis and maintenance of the installations [8, *Power & Programming/ Fountain Controller*], including a water level sensor and a Wind Level Control unit (WLC) with anemometer. According to the water level sensor recordings, the drainage pump starts operating if the water level exceeds the maximum level, or the fill-valve allows filling the pool through a water supply pipe if the minimum water level is reached. The WLC allows setting wind-dependent water patterns, or shutting down all fountain pumps for excessive wind speeds – e.g. above the reference wind speed of 26 m/s, where the average wind speed exceeds 14m/s, and Beaufort number is equal to 7.

Each water jet is individually fed, upon a scheme as the one in fig. 2a, which is a cross section through the underground pool (Fig. 2b). The distance from the Bottom level (inferior part of the metallic frame on which the pumps are mounted) to the Reference level (ground level), defined further as gap depth, is $h_g = 0.78$ m. The water depth, from the pool's free surface to Bottom level, varies between 0.5 m (for minimum water level) and 0.6 m (for maximum water level).

From the beginning of April to the end of October, the fountains operate daily, 11 hours per day, from 10 a.m. to 10 p.m., with one hour imposed stop from 1p.m. to 2 p.m. In summer days, during this one-hour pause, the pool is filled with fresh water up to the maximum level. In this paper, we assume that the water level is kept constant, at its maximum value, where the water depth is $h_w = 0.6$ m.

The *Varionaut 150/DMX/02* fountain pump [8] is a centrifugal pump with semi-closed impeller, operating with variable speed; the maximum power consumption is of 130 W. The pump is equipped with submersible power supply cable (230 V AC, 50 Hz), as well as cable and underwater connection box to the DMX-RDM controller (where DMX means Digital Multiplex communication protocol, and RDM stands for Remote Device Management). Through a DMX connection, each pump is speed-regulated and controlled; a second DMX/RDM connector allows the interconnection with other pumps and LED spotlights.

By varying the pump speed, thus the discharge and consequently the jet height, dynamically changing water flow patterns can be generated using a programmable controller [8]. The above pump can generate a water jet upon a highly dynamic water pattern, with repeatable heights of the ejected jet. Together with a *Comet 10-12* nozzle, the pump can shoot a water jet up to 3.5 m height in just 1 second, at nominal speed [8]; due to the fact that the full jet height is reached by switching frequency from 0 to 100% in just 1 second, the *Varionaut 150/DMX/02* pump is characterised by very dynamic speed behaviour.

The electronic motor that drives the pump (230 V EC-Motor) operates at nominal speed $n_0 = 3920$ rpm at 50 Hz; its speed can be adjusted by a frequency converter; the minimum speed is $n_m = 800$ rpm, at 10.2 Hz. The pump performance curve at speed n_0, namely pumping head H_0 [m] vs flow rate Q_0 [litres/s], is plotted in fig. 4, based on manufacturer's data [8].

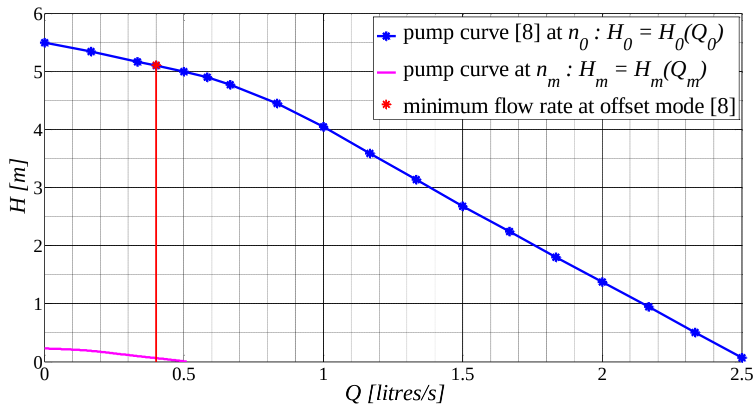

Fig. 4. Pump performance curves at nominal speed n_0 (blue markers [8]) and at minimum speed n_m (pink line), and minimum flow rate limit at offset mode (red marker/line)

The performance curve $H_m = H_m(Q_m)$ at the minimum speed n_m was also plotted, using the affinity laws [5]: $Q_m = (n_m/n_0)Q_0$ and $H_m = (n_m/n_0)^2 H_0$. At offset mode ($\text{DMX} = 0$), the minimum value of the flow rate is 0.4 litres/s [8]. No efficiency curve was provided for the above pump.

At the pump discharge, there is an outside thread G1½ inch connection. A reducing sleeve with inside thread G1½ – G1 inch is mounted between pump's discharge and inlet of a telescopic nozzle extension (sleeve's length is 0.05 m; its inner diameter is reduced from 42 to 27 mm). The telescopic nozzle extension is deployed up to the A-type nozzle inlet, on a length of 0.42 m; its estimated inner diameter is 27 mm. Geometrical data of the A-type nozzle *Comet 10-12 Silver* [8] are: inlet with outside thread G1 inch connection (of estimated inner diameter $D = 27$ mm), nozzle length of about 0.12 m, and outlet orifice of inner diameter $d = 12$ mm. From the nozzle outlet up to node 3 (ground level), the spotlights central opening has the inner diameter $d = 12$ mm and estimated length of 0.02 m; thus, the distance from node 2 to node 3 is $h_s \cong 0.14$ m.

The hydraulic performances of the nozzle *Comet 10-12 Silver* are presented in Table 1 [8], in terms of water demand Q_n (values in litres/min) and pressure head H_n (in metres), required at the nozzle inlet (node 2), to attain the reported values h_e of the jet height (in metres).

Table 1

Hydraulic performances of *Comet 10-12 Silver* nozzles [8]: nozzle water demand Q_n [litres/min] and pressure head H_n [m], required to generate a jet up to height h_e [m]

reported jet height h_e	[m]	0.5	0.75	1	1.25	1.5	2	2.5
water demand Q_n	[litres/min]	21	25	31	35	39	46	53
pressure head H_n	[m]	0.61	0.82	1.12	1.43	1.73	2.34	2.96
reported jet height h_e	[m]	3	3.5	4	5	6	7	8
water demand Q_n	[litres/min]	58	63	68	76	84	91	98
pressure head H_n	[m]	3.57	4.28	4.89	6.22	7.54	8.87	10.19

Although it is not specified in the available documentation, further computations reveal that the reported h_e values were measured starting from the inlet of the vertical nozzle (node 2). Thus, the jet height h above the ground level can be obtained for the studied geometrical configuration as: $h = (h_e - h_s)$.

The pressure head at node 2 is defined as: $H_n = p_n/(\rho g)$, where p_n is the gauge pressure at the nozzle inlet, ρ is the water density and g is the gravity.

3. Dry Fountains of UPB: Numerical model and theoretical approach

An equivalent numerical model of the *Dry Fountains of UPB* was built (figure 5), to simulate the operation of those fountains. The numerical model contains the following components (listed upon the flow direction):

- an open water pool R of constant head, which value equals the value of the water depth $h_w = 0.6$ m; the point 1 from fig. 5 is on the free surface of the pool;
- 12 fountain pumps P1÷P12, supplied from pool R; since only the performance curve $H_0(Q_0)$ at nominal speed n_0 was provided by the manufacturer, an estimated efficiency curve will be proposed further; each pump P_i (with pump index $i = 1 \div 12$) is driven with variable speed n_i, theoretically within the range $n_m \le n_i \le 1.2 n_0$, meaning within the speed factor range $0.204 \le \omega_i \le 1.2$ (where the speed factor is defined as $\omega_i = n_i/n_0$); each pump P_i operates upon its own

speed pattern $\omega_i = \omega_i(t)$, where t is the time; all speed patterns will be derived further to mimic the dancing water jets, according to a recorded water show full sequence; the discharge of each pump is set at 0.17 m elevation with respect to Bottom level (fig. 2a);

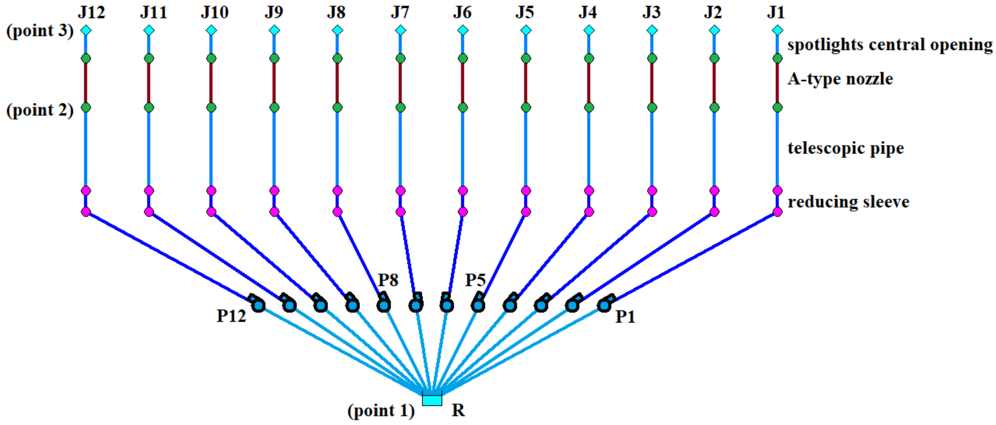

Fig. 5. *Dry Fountains of UPB* numerical model: water pool R (point 1 on its free surface); pumps P1÷P12; 3 pipes on each hydraulic circuit (reducing sleeve, telescopic pipe and spotlights central opening); A-type nozzles with inlet nodes as point 2; outlet orifices (point 3); water jets J1÷J12

- the discharge of each pump is connected to a short pipe of 35 mm inner diameter and 0.05 m length, which replaces the reducing sleeve; the telescopic pipe is set with 27 mm diameter and 0.42 m length; the roughness of both pipes is 0.01 mm;
- 12 A-type nozzles; each nozzle is connected between two nodes: the start-node is point 2 (set at 0.64 m elevation); the end-node is the nozzle outlet (at 0.76 m elevation); a minor losses regression curve $h_m(Q)$ will be derived further for this nozzle, based on minor losses h_m values computed from available data (Table 1);
- the outlet of each nozzle is connected to a short "exit pipe" (spotlights central opening), which is set with inner diameter $d = 12$ mm, length of 0.02 m and roughness of 0.01 mm; the end-node of this "exit pipe" (point 3, placed at 0.78 m elevation) is the outlet orifice from where the jet rises.

All computations were performed in GNU Octave [4] (the best-known alternative to MATLAB), with flow rate in m^3/s; for easy reading, graphics are plotted with flow rate in litres/s. Head losses are computed with Darcy-Weisbach formula, where the friction factor is defined by Swamee & Jain formula [5].

The pump performance curve $H_0 = H_0(Q_0)$ at nominal speed n_0, plotted in fig. 4 based on available data (blue markers) [8], can be fitted by a 7th order polynomial regression curve (blue line in fig. 4). For the operating flow rate range of the fountains, $Q_0 \in [0.4 \cdot 10^{-3}; 1.1 \cdot 10^{-3}]$ m^3/s, the above curve can also be fitted by a second order polynomial, with coefficients $c_1 = -1.43 \cdot 10^{-6}$, $c_2 = 260.17$ and $c_3 \cong 5.23$. Therefore, the pump performance curve $H = H(Q, \omega)$ at any speed factor ω (with ω as parameter) is defined based on affinity laws [5], as:

$$H(Q, \omega) = c_1 Q^2 + c_2 \omega Q + c_3 \omega^2 , \tag{1}$$

where the pumping head H is obtained in metres for the flow rate Q in m^3/s. For $\omega = 1$, the regression (1) fits the curve $H_0 = H_0(Q_0)$.

For the considered centrifugal pump, the efficiency curve $\eta = \eta(Q, \omega)$, derived at any speed factor ω using the affinity laws [5], can be estimated by the following 4th order polynomial regression curve:

$$\eta(Q) = c_4 (Q/\omega)^4 + c_5 (Q/\omega)^3 + c_6 (Q/\omega)^2 + c_7 (Q/\omega) + c_8 , \tag{2}$$

where $c_4 = -7.64 \cdot 10^{13}$, $c_5 = 3.03 \cdot 10^{11}$, $c_6 = -4.54 \cdot 10^8$, $c_7 = 3.04 \cdot 10^5$, $c_8 = 0$; the efficiency η is expressed in percents [%] for the flow rate Q in m^3/s. To simplify notations, the pump index i was not added in (1) and (2).

In order to study the operation of *Dry fountains of UPB*, the theoretical approach is developed on 4 main steps:

① determination of the variation of the minor losses h_m versus the flow rate Q, within the A-type nozzle *Comet 10-12 Silver,* based on the jet height values reported by the manufacturer for that particular nozzle (Table 1);

② determination of the hydraulic system curve $H_s = H_s(Q)$, where H_s is the system head, issued from the energy law applied between the inlet and the outlet of the hydraulic circuit; determination of duty points F (pair of flow rate Q_F and pumping head H_F values) that can be attained by each pump, at the intersection between the pump performance curve (1) and the system curve;

③ determination of the jet height pattern, $h = h(t)$ for each nozzle, from J1 to J12, based on the video recording of a water show full sequence;

④ determination of the speed pattern $\omega = \omega(t)$ of each pump, which ensures the corresponding jet height pattern; determination of the overall energy consumption requested to produce the water show sequence.

① Minor losses within the selected A-type nozzle

There are different definitions that allow appreciating the height of a water jet that rises vertically from an orifice with circular section in a horizontal plane. Within the studied system, where the water flow rate Q (in m^3/s) is pumped through a vertical nozzle with outlet orifice of inner diameter d in metres (here $d = 0.012$ m), the above heights are expressed (in metres) as:

- theoretical jet height, $h_t = \left(8/(\pi^2 g)\right) Q^2 / d^4$;
- height of the highest drops, $h_{hd} = \left(1 - 0.113\, h_t /(1000\, d)\right) h_t$ [14], written as

$$h_{hd}(Q) = \left(1 - 0.113 \cdot 10^{-3} \frac{8}{\pi^2 g} \frac{Q^2}{d^5}\right) \frac{8}{\pi^2 g} \frac{Q^2}{d^4}; \tag{3}$$

- compact jet height (or effective height of the jet), $h_c = (2/3) h_{hd}$ [14].

For the selected A-type nozzle, the corresponding curves $h_t(Q)$, $h_{hd}(Q)$, $h_c(Q)$ are plotted in Fig. 6. For comparison, the reported jet height values $h_e(Q)$ from Table 1 [8] are added on the graphic from fig. 6, using red markers.

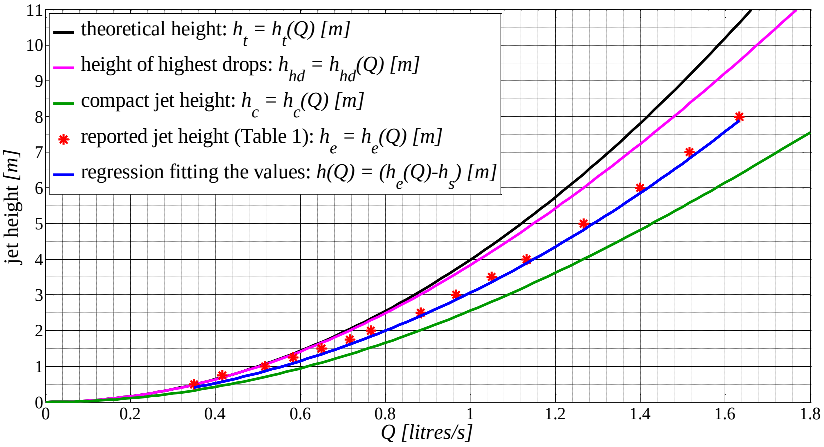

Fig. 6. Jet height [m] vs flow rate Q [litres/s]: h_t; h_{hd} (3); h_c; h_e (red stars), and h (blue line)

Taking into account the studied system geometry, the jet height h above the ground level is computed as: $h(Q) = \left(h_e(Q) - h_s\right)$, where $h_s \cong 0.14$ m. The resulting h values can be fitted by a 2nd order polynomial regression curve $h(Q)$, which is plotted in fig. 6 (as blue line); for the proposed regression curve, the computed jet height h fits the relation $h_c < h < h_{hd}$ at any flow rate. For small flow rates, e.g. for $Q < 0.5 \cdot 10^{-3}$ m^3/s, the reported jet height values are obviously too big: $h_e > h_t$; this is the reason for assuming (as previously stated) that the h_e values were measured by the manufacturer starting from the inlet of the nozzle.

The minor losses h_m within the A-type nozzle *Comet 10-12 Silver* can be obtained from Bernoulli's equation, written between the nozzle inlet (node 2) and the upper part of the jet (node 4 in fig. 2a), based on data from Table 1:

$$h_m(Q) = H_n(Q) - h_e(Q) + \frac{8}{\pi^2 g}\frac{Q^2}{D^4} - h_f(Q), \tag{4}$$

where h_f are the head losses on the short "exit pipe" (spotlights central opening). The values $h_m(Q)$ computed with (4), together with $h_m(0) = 0$, can be fitted by a 4th order polynomial regression, with coefficients $b_1 = -3.6 \cdot 10^{11}$, $b_2 \cong 1.4 \cdot 10^9$, $b_3 \cong -6.71 \cdot 10^5$, $b_4 \cong 310.77$ and $b_5 = 0$, as:

$$h_m(Q) = b_1 Q^4 + b_2 Q^3 + b_3 Q^2 + b_4 Q + b_5, \tag{5}$$

where h_m is computed in metres for Q in m^3/s,.

② Hydraulic system curve and resulting duty points

Within the studied hydraulic system, each fountain pump operates at its duty point F, defined by the rated flow rate Q_F and rated pumping head H_F (to simplify notations, pump's index i was not added here). From graphical viewpoint, the duty point F is found at the intersection between the performance curve $H = H(Q, \omega)$ at a given value of the speed factor ω, and the system curve $H_s = H_s(Q)$, where H_s is the system head. The energy law can be written between point 1 on pool's surface, and point 3 at the outlet orifice (fig. 5), as:

$$h_w + H(Q,\omega) = h_g + 8Q^2 / \left(\pi^2 g\, d^4\right) + \left(h_r(Q) + h_t(Q) + h_m(Q) + h_f(Q)\right), \tag{6}$$

where h_r and h_t are the head losses on the short pipe that replaces the reducing sleeve, and on the telescopic pipe respectively; the pumping head is defined by (1) and minor losses are defined by (5).

By denoting the system curve as:

$$H_s(Q) = \left(h_g - h_w\right) + 8Q^2 / \left(\pi^2 g\, d^4\right) + \left(h_r(Q) + h_t(Q) + h_m(Q) + h_f(Q)\right), \tag{7}$$

the energy law (6) can be rewritten in compact form as: $H(Q,\omega) = H_s(Q)$. The graphical representation of the energy law, meaning the intersection between the pump performance curve and the system curve, is presented in Fig. 7 for the following speed factor values: $\omega \in \{1; 0.9; 0.8; 0.7; 0.6; 0.5\}$.

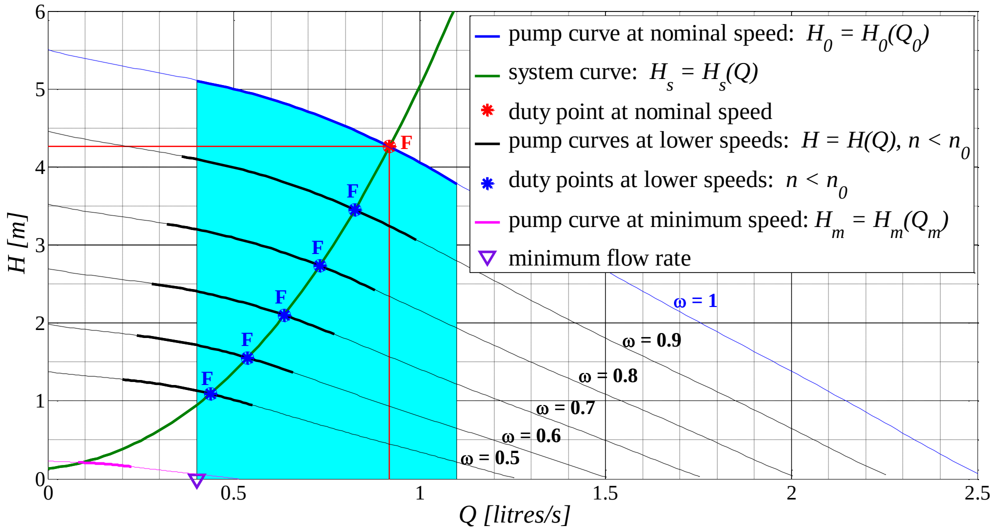

Fig. 7. Pump performance curves for $0.5 \le \omega \le 1$, system curve and duty points F

The values of the operating parameters $\{Q_F; H_F\}$ attached to each duty point F are inserted in Table 2; the efficiency given by (2) is $\eta_F \cong 76.62\%$ for all points. For any speed factor $\omega < 0.465$, the pump is stopped, because the pumped flow rate is smaller than allowed: $Q_F < 0.4$ litres/s. That means that for the studied system, a pump can be set open within the speed range: $0.47 < \omega \le 1.2$.

Table 2

Operating parameters attached to pump's duty point F at different speed factor values:

	$\omega = 1$	$\omega = 0.9$	$\omega = 0.8$	$\omega = 0.7$	$\omega = 0.6$	$\omega = 0.5$
Q_F [litres/s]	0.918	0.825	0.731	0.635	0.538	0.437
H_F [m]	4.26	3.45	2.73	2.10	1.55	1.09

③ Jet height patterns

Due to lack of data from the installed water entertainment control system, the jet height patterns are derived for a water show full sequence, upon video recordings. When fountains are operating, the water show is repeated, yielding the same water flow pattern, over the total duration of $3:00$ [min : sec]. Recordings made from mid to end July 2021, and at the beginning of September 2021, gave repetitive results with respect to the jet heights averaged values per time step, for similar low wind speed conditions (from calm to light breeze).

The movie analysed here corresponds to a water show full sequence of 180 seconds total duration. During the first 28 seconds, only few jets appear, separated by very short pauses without ejected jets. So, 159 relevant frames were extracted from the movie (by video image capture), initially with 3 seconds time step, then with 1 second step. Each image was analysed in AutoCAD, and all 12 jet heights $h(t)$ [m] were measured at each time t, after a proper scaling (based on the distance of 1.00 m between 2 consecutive jet axes), as in Figs. 3 and 8.

For the time interval $1:46 \le t \le 2:18$ [min : sec], thus during 33 seconds, all jets rise at the same mean value of the height, due to the same speed value set for all pumps. As shown in fig. 8, at time $t = 2:01$ [min : sec], the measured $h(t)$ values are not equal, but different from one jet to another: they vary from 3.48 m at J5, to 3.68 m at J12, the mean value for all jets being $h = 3.55$ m. Although the pump speed is kept constant during those 33 seconds, the jet heights also vary for the same nozzle – the reason may rely on instabilities induced by the water level variation in the pool. For the above time interval, the total number of 33×12 jet height values gives an overall mean value $h \cong 3.55$ m. For the 3 minutes water show sequence, the analysed movie gives a total number of $159 \times 12 = 1908$ jet height values $h(t)$, where the maximum $h(t)$ value varies from 3.77 m (at J1, J3, J5, J6) to 3.86 m (at J11); the averaged maximum value is $h = 3.79 \cong 3.8$ m.

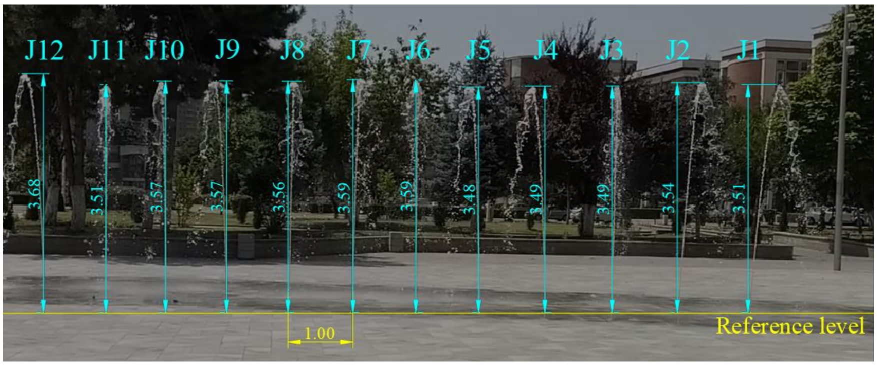

Fig. 8. Jet height h in [m], measured for jets J1÷J12, at time moment $t = 2:01$ min:sec

④ Speed patterns and overall energy consumption

For all 12 nozzles, the measured jet heights $h(t)$ were inserted into a 159×12 size matrix, where lines denote time t and columns denote jets J1÷J12. The corresponding pumped flow rate $Q_F(t)$ is the solution of the following equation, derived from the height of the highest drops (3):

$$\left(1 - 0.113 \cdot 10^{-3} \frac{8}{\pi^2 g} \frac{Q_F^2(t)}{d^5}\right) \frac{8}{\pi^2 g} \frac{Q_F^2(t)}{d^4} - h(t) = 0 . \tag{8}$$

Further, from the energy law (6), combined with (1) and (5), where the flow rate is known: $Q \equiv Q_F(t)$ in m^3/s, the speed factor value $\omega(t)$ is obtained for the corresponding pump (P1÷P12). Finally, knowing the values $\{Q_F(t), \omega(t)\}$, the pumping head $H_F(t)$ in metres and efficiency $\eta_F(t)$ expressed in percents can be computed using (1) and (2).

The power $P_F(t)$ consumed by the considered fountain pump is defined as: $P_F(t) = \rho g Q_F(t) H_F(t) / \eta_F(t)$ [W], based on dimensionless efficiency. To simplify notations, the jet/pump index $i = 1 \div 12$ was not added for variables h, Q_F, ω, H_F, η_F, and P_F, but this index will be added further. Accordingly, the overall energy E consumed for pumping to produce a water show full sequence is:

$$E = \sum_{t=0:00}^{t=3:00} \left(\sum_{i=1}^{i=12} P_{Fi}(t)\,\Delta t \right), \tag{9}$$

where Δt is the corresponding pump operation time step [seconds].

As previously described, the *Dry Fountains of UPB* operate 11 hours per day (thus 220 water show full sequences are repeated daily), minimum 214 days per year (7 months: April÷October). The electric energy consumed for pumping to ensure fountains' operation per day (denoted E_d), per month and per year can be finally computed (converted in kWh).

4. Results and discussions

Following the theoretical approach (Section 3), speed patterns $\omega_i = \omega_i(t)$ were computed for all pumps P_i ($i = 1 \div 12$), for $t = 1 \div 180$ seconds. The resulted speed patterns are plotted in Fig. 9 for pumps P1÷P12.

The following values were obtained for the energy consumption attached to the fountain pumps: $E = 74.36\ \text{kJ} \cong 0.02\ \text{kWh}$ per water show full sequence, $E_d = 4.54$ kWh per day, about 139 kWh per month, and 972.5 kWh per year.

The present study focuses exclusively on the overall energy consumed for pumping to produce the desired water show sequence. Additionally, there is also some amount of energy that is daily consumed by the fountains controller and all 12 LED spotlights, as well as by the auxiliary systems that ensure the water recirculation, filtration and treatment. Temporarily, some energy is also consumed for drainage. The energy consumption is quite low for spotlights and controller, but the recirculation pump is an important consumer: its power of about 110 W leads to about 1.2 kWh energy consumption, which means 26.4 % from E_d value. Accordingly, one can assume that the auxiliary systems and devices contribute to the total daily energy consumption with about 30% from E_d. This assumption gives the following estimated values of the total energy consumed by the entire system: about 6 kWh per day, about 180 kWh per month, and 1264 kWh per year.

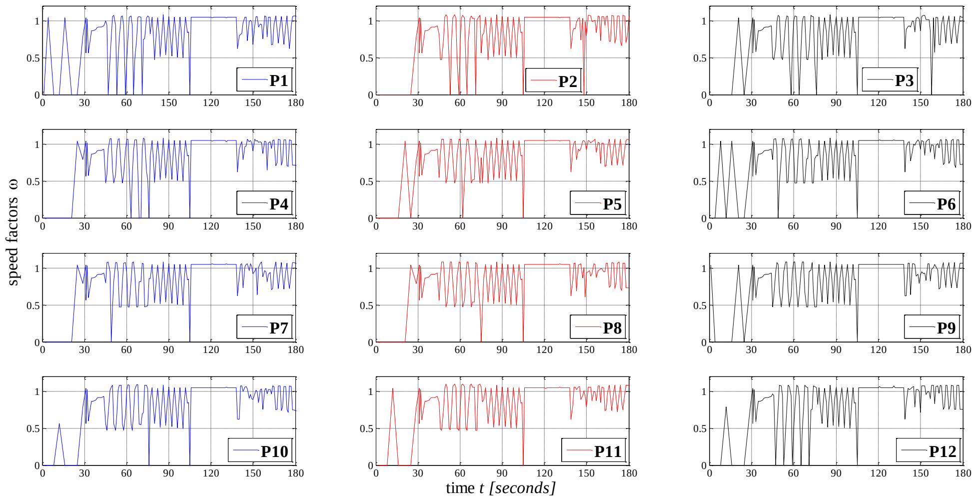

Fig. 9. Computed speed patterns: speed factors $\omega = \omega(t)$ for pumps P1÷P12

5. Conclusions

The case study analysed in this paper relies on the *Dry Fountains of UPB*, which consist of 12 water jets, aligned on a single straight line of 11m length. Fountains operation was modelled using GNU Octave and AutoCAD, to mimic a 3 minutes water show sequence, where jets rise dynamically from pavement up to about 3.8 m, with different water effects (pop-up, wave effect and splash). Based on the computed overall energy consumed by 12 variable speed driven pumps to produce 12 dancing jets, and knowing that 220 water show sequences are repeated daily (11 hours/day), for at least 214 days/year (during the warmest months of the year), the values of the electric energy consumed for pumping per day, month and year were finally computed. Although only the energy consumed by the fountain pumps was computed in this paper, and the energy required by auxiliary systems was only estimated, the resulted values of the total energy consumption of 180 kWh per month (from April to October) and 1264 kWh per year are useful for *UPB's Aula* building energy management system (fountains' equipment and electric devices are directly connected to building's electric grid, without separate metering of the electric energy consumed by the fountains). *UPB's Aula* is a very modern facility, recently built (commissioned in 2018), with a capacity of 1200 places. The energy consumed by the fountains is just a fraction of the total energy consumed and recorded in this building, where the HVAC system is the biggest consumer. Nevertheless, the results provided here can support the building energy management system, when assessing fountains' impact on the electricity bill.

The theoretical approach proposed in this paper can be used to compute the electric energy consumption of any configuration of dry fountains, based on hydraulic and mechanical parameters, if the system geometry and equipment technical specifications are known. Although the present study corresponds to a reverse engineering problem, where starting from an existing water show, the pumping power consumption was assessed, the same approach can be used to design new dry fountains, or different water shows for existing dry fountains.

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