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1. Energy transfer improvement in a water pumping installation

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1.1. Introduction

Water and energy are two main topics among the nowadays challenges for engineers and scientists, in the context of the increasing population, growing wealth and consumption, and intensive climate change all over the world. The 2016 International Water Association Forum organized in Brisbane identified six focus areas, stating that "rebuilding all existing infrastructures is unrealistic, we must focus on optimization and efficiency gains in current practices" (Brisbane Report, 2016).

Pumping installations, providing drinking or irrigation water are among the most important energy consumers, therefore it is determinative for the hydraulic system not only to meet the required technical parameters but also to provide a high level of energy efficiency.

Engineers focus on both the reduction of energy consumption and the efficiency improvement of the end consumers, such as electrically driven hydraulic pumps. An energetic perspective on the pumping stations has to take into consideration the pumps and the pipelines as well (Constantin et al. 2012).

The study is oriented on both branched and looped water supply systems in rural area, aiming to assess the hydraulic parameters in different operation alternatives and to determine by numerical simulation the most appropriate and energy efficient operation method of the pumping installation.

1.2. Theoretical considerations on hydraulic energy

Hydraulic energy is defined as the capacity of a liquid to do work as it flows from one state to another. Usually, in technique, energy is not available in the needed form, therefore it must be transformed by the use of specific machinery. Hydraulic pumps are designed to convert mechanical energy into hydraulic one. The electrically driven dynamic pumps, which are mostly used in water supply, cause a continuous fluid movement due to a rotating part: an impeller or a propeller. In a pumping unit, meaning the pump and its electrical motor, energy conversion takes place in two steps: firstly the electric energy is transformed by the electric motor into mechanical one, and secondly the mechanical energy is transformed by the impeller into hydraulic energy given to the fluid. As the fluid passes through the impeller, its velocity increases. The flow continues through the pump's casing, and the velocity is reduced, because part of the kinetic energy is converted to potential energy. For both motor and pump, energy conversion has a certain efficiency, thus an overall efficiency may be defined:

$$\eta = \eta_e \cdot \eta_p \tag{1.1}$$

Where:

η_e – efficiency of the electric motor, [-];
η_p – pump's efficiency, [-].

The pumping head, the difference between the specific energy in and out the pump, is the most important technical parameter and corresponds to a given discharge. Subtracting the pump's internal losses from the total theoretical head stated by Euler, at different flowrates, will yield the pump's curve, which for the centrifugal type is a parabola. Furthermore, this parabola can be expressed as a function of discharge and rotation speed (Constantin et al., 2011):

$$H_{(Q,n)} = aQ^2 + bnQ + cn^2 \tag{1.2}$$

Where:

H – total head, [m];
Q – discharge, [m³⁄s];
n – rotation speed, [rot⁄min];
a,b,c – constant coefficients.

Pumps and pipelines should operate together in a hydraulic system such a way that the energy given by the pumps to the fluid to be enough for it to overcome the static head and the resistance to movement opposed by the pipelines.

The system curve represents the energy requested by the pipelines and their equipment (valves, elbows etc.) in order to transport different values of flowrate.

$$H_c = H_g + h_r \tag{1.3}$$

Where:

H_g – geodetic head, [m];
h_r – head loss over the pipelines, [m].

In a pumping installation, water flow is turbulent, therefore the head loss is proportional to the squared flowrate:

$$h_r = MQ^2 \tag{1.4}$$

Where:

M – hydraulic resistance modulus for all the pipelines in the pumping installation, $[m^{-5}s^2]$.

The equivalent hydraulic resistance modulus for the entire pumping installation, can be calculated according to the way the pipes are connected: series or parallel. A given pump operates on a specific system of pipes at the flowrate for which the energy generated by the pump equals the energy requested by the system.

Thus, for each discharge value given by a pump, we have the relationship (Constantin 2016):

$$H_g + MQ^2 = aQ^2 + bnQ + cn^2 \tag{1.5}$$

Or, stated differently, the duty point, ***F***, is the intersection between the curves (1.2) and (1.3)., as it is shown in Fig.1.1.

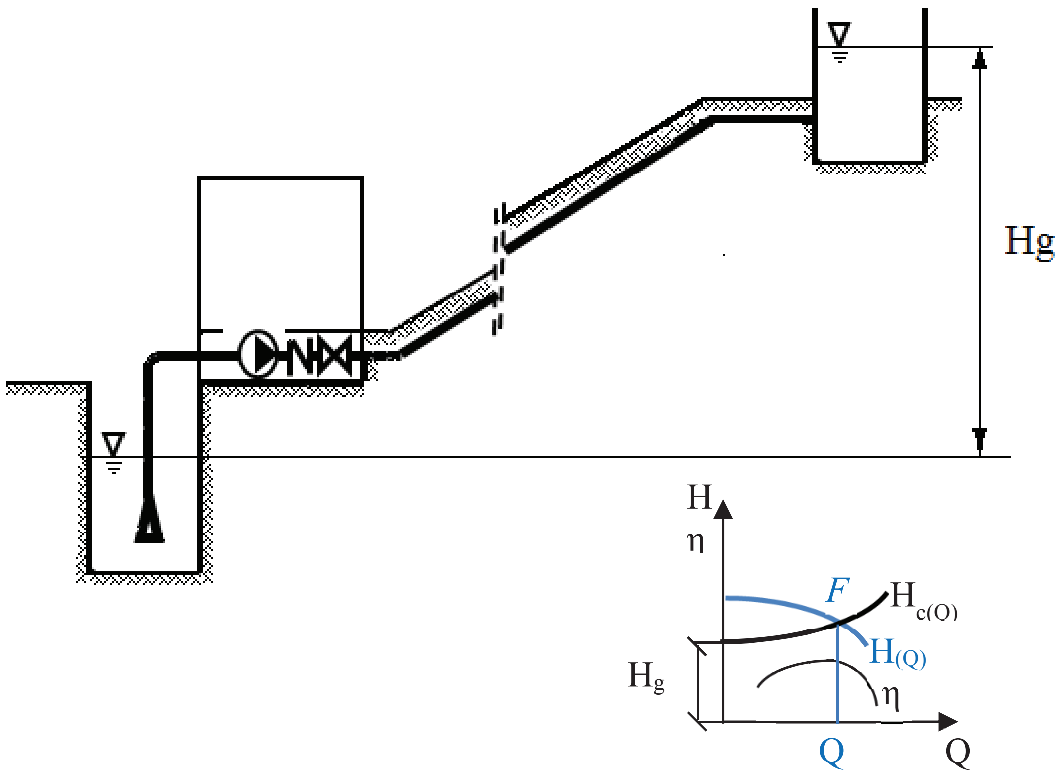

Fig. 1.1. Pumping installation. Duty point F

A pump selection is a matter of accuracy, depending on either the available pumps offered by the pump building companies or the skills of the engineer who designs the hydraulic system. A pump is chosen according to the water demand of the consumer and the maximal total head requested by the system, assessed by the designer. It is recommended the consumed power to be as low as possible.

When an installation is equipped with a single pump, this has to be chosen at its best operation point that means, at maximal efficiency. But one single pump on a system is not a good choice (unless the pump has variable speed) because the variable demand of the consumer has to be followed by the pump discharge during operation. The flow rate delivered by a constant speed pump can be varied only by controlling the opening of the valve on the discharge duct, which is an increased energy consuming method. Therefore a group of pumps working in parallel is the usual option.

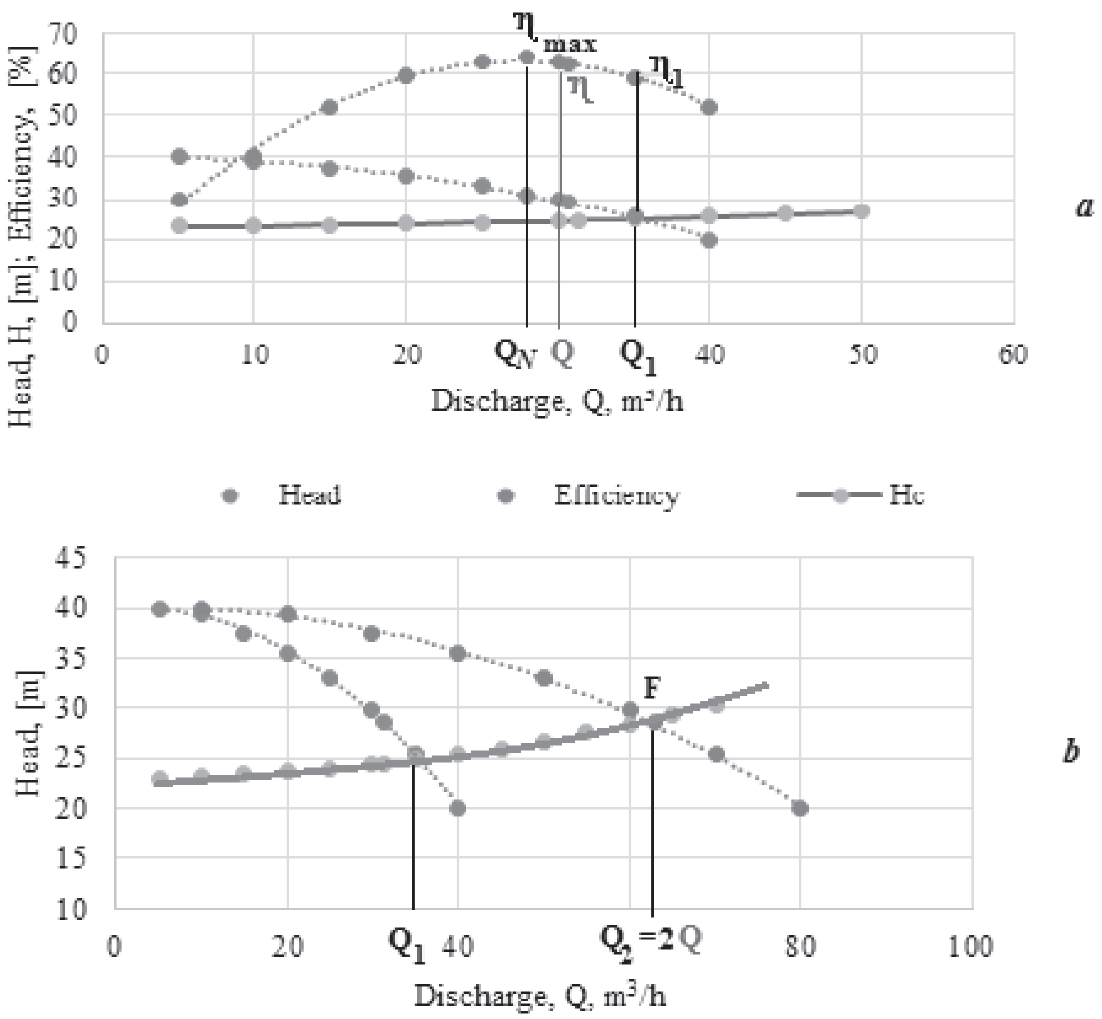

Fig. 1.2. Efficiency variation according to the discharge of the pump a.one pump operation; b. two identical pumps operating in parallel

For instance, when two identical pumps, with constant speed, operate in parallel the discharge provided by the installation can be set on two different values. When the two pumps are different, one additional value can be obtained for the discharge. Other values for the discharge can also be obtained solely by throttling.

In the case of two pumps mounted in parallel, the efficiency and the consumed power depend on whether one or two pumps are operating.

Let's consider two identical centrifugal pumps with constant speed, mounted in parallel. The valves on the discharge ducts stay completely open. The pump has been selected for a duty point with the discharge Q at the total head H and the efficiency η, as represented in Fig.1.2a. Its best operation point (BOP) is placed at a smaller discharge $Q_N < Q_1$. Its maximal efficiency is η_{max}.

When operating in parallel, the two pumps will deliver the discharge $Q_2 = 2Q$ at the head H that means we refer to the duty point F, in Fig.1.2*b*. Their efficiency will be also η, assuming the pipelines are symmetrical from hydraulic point of view. But when a single pump operates, its duty point moves to a bigger discharge,$Q_1 > Q$, thus the efficiency decreases to $\eta_1 < \eta < \eta_{max}$, Fig.1.2*a*.

The average efficiency such a group of centrifugal pumps will operate with, depends on how long they will work together. The case depicted by Fig.2 is recommended as the pumps will work in parallel a longer period than separately. Conversely, when the two pumps work in parallel a shorter period than separately, the best operation point is recommended to be placed at a bigger value of the discharge than the duty point that type of pump was selected for.

The best discharge adjustment method, from energy efficiency view point, is possible by varying the rotation speed, if the pump allows it. Variable speed pumps are expensive, but they allow a rational use of the energy during pumping installation operation.

A variable speed pump performances can be determined with the affinity laws (Burchiu 1982):

$$\frac{Q_x}{Q} = \frac{n_x}{n} \tag{1.6}$$

$$\frac{H_x}{H} = \left(\frac{n_x}{n}\right)^2 \tag{1.7}$$

$$\frac{P_x}{P} = \left(\frac{n_x}{n}\right)^3 \tag{1.8}$$

$$\eta_x = 1 - (1 - \eta)\left(\frac{n}{n_x}\right)^{0,2} \tag{1.9}$$

These laws allow us to calculate the speed n_x, the head H_x and the power P_x for a desired discharge Q_x, when all these parameters are known for a speed *n*. Usually the manufacturers build the same pump model with constant and with variable speed.

A variable speed pump can deliver the same discharge Q_3 either in the duty point F_2 at maximal speed, n_1, or in F_3, at a smaller speed, n_3, but the power is different due to the difference between the heads H_2 and H_3, Fig.1.3. The difference in power is shown by the difference between the areas of red and green rectangles in Fig.1.3. If the considered pump was a constant speed one, operating at $n_1 = ct$, at the duty point F1, its discharge could be decreased to Q_3 only by partly closing its valve on the discharge duct.

In the pumping installations equipped with variable speed pumps, two pumping methods are possible:

- by keeping the pressure proportional to the delivered flow rate (duty points F1 and F3 on a parabola shaped system curve with no static head, Fig.1.3);
- by keeping the pressure constant as the delivered flow rate varies.

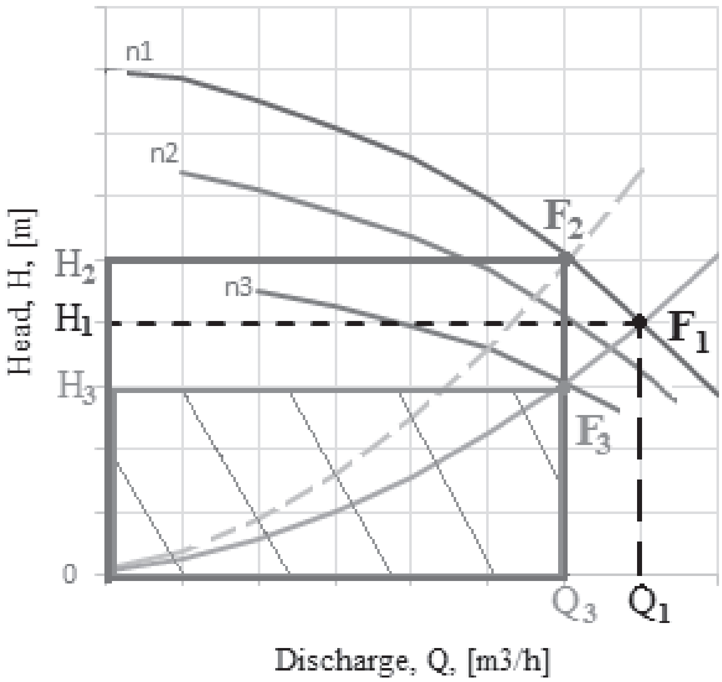

Fig. 1.3. Duty point, F_1 is homologous with F_3. If F_1 is BOP, the duty point F_3 will have a better efficiency than F_2. Example for BOP placed to the right of the duty point the pump was chosen for

1.3. Numerical simulation

Numerical simulation in EPANET is a free means for assessing the hydraulic parameters in different operation alternatives of a new designed network or an existing one that has to be modernized. It allows us to correct random sizing flaws, if any, and to determine the most appropriate and energy efficient pumping method. Simulation assisted design and operation are more and more affordable and consequently more used, therefore efforts on simulation uncertainty evaluation methods are being done (Nopens, 2016). Nevertheless simulation has to be conducted by people who have a solid background in the field.

EPANET considers all the components of a water supply system as junctions or pipes. Water demand is concentrated in junctions, therefore there is no distributed demand along the pipe. Hydraulic system's operation can be simulated as steady or unsteady and also the water quality can be investigated in different scenarios (Rossman, 2000).

The EPANET software imposes the demand flow rate in the junctions of the network and calculates the required head values. The results with respect to pressure, velocity, flow can be collected as fields of data or as time series.

Smârdan village drinking water distribution network has been chosen as study case, in order to be modernized. This village is located, at a relatively low and uniform elevation, close to the Danube, Fig. 4.

The water distribution network in Smârdan is a looped type, directly supplied by a pumping station (NP 133-2013). The underground pipes follow the streets direction in the village, as they are shown in Fig.4.

The sizing flow rate is 17.03 l/s, in accordance with the number of inhabitants, fire water volume and the developing perspective of the village (NP 133-2013).

Fig. 1.4. Village Smârdan, on the Danube river side

It represents 12% of the maximal water demand during a day. A high variation of the water demand during a day is specific for a rural settlement. According to the recommendations (SR 1343-1/2006), the standard hourly water demand variation indicates thirteen different discharge values which should be provided by the pumping station during a day time.

The simulation was carried out for the existing configuration of the network-looped network. A second configuration was taken into account: branched network, aiming to compare them. All the metallic pipes were replaced by PEHD pipes.

For each of the two configurations, simulation was done considering the network supplied by:

- two identical constant speed pumps,
- two identical variable speed pumps.

Hydraulic analysis was made during 24 hours.

The constant speed pump selected for the looped network gives the discharge of 30.65 m^3/h at a total head of 29m, with a efficiency of 62.4% . Its BOP is at 30 m^3/h with an efficiency of 63%. The constant speed pump selected for the branched network gives the same discharge of 30.65 m^3/h at a total head of 23m, with a smaller efficiency of 59.5%. Its BOP is at a bigger discharge, of 38.6 m^3/h, with the same efficiency of 63%. The variable speed pumps were considered the same model, and with respectively the same performances at maximal rotation speed as those with constant speed.

1.4. Simulation results. Discussion

The simulation for either looped or branched network supplied by constant or variable speed pumps led to a complete image of the hydraulic parameters. Smârdan proved to be a low pressure network.

In the case of looped network supplied by constant speed pumps, pressure field showed that during night time, when the demand is very low, pressure in nodes is high, reaching 41,4 mwc , which is below the upper limit of 60mwc (SR 1343-1/2006).

The existing looped configuration is represented in Fig.15. The corresponding hydraulic resistance modulus for the looped network is $M_l = 80900\ [m^{-5}s^2]$.

The velocity field revealed a variation between 0.43 to 0.81 m/s. During the night when the demand is low, velocity decreases down to 0.04 m/s in a few peripheral pipes.

A special attention was paid to the furthest consumer, i.e. node 25, with a base demand of 1.72 l/s. The demand variation during 24 hours is graphically given in Fig.1.6 a. The constant speed pumps were chosen such way the pressure in this node to be at least 7mwc, as imposed for the hydrants.

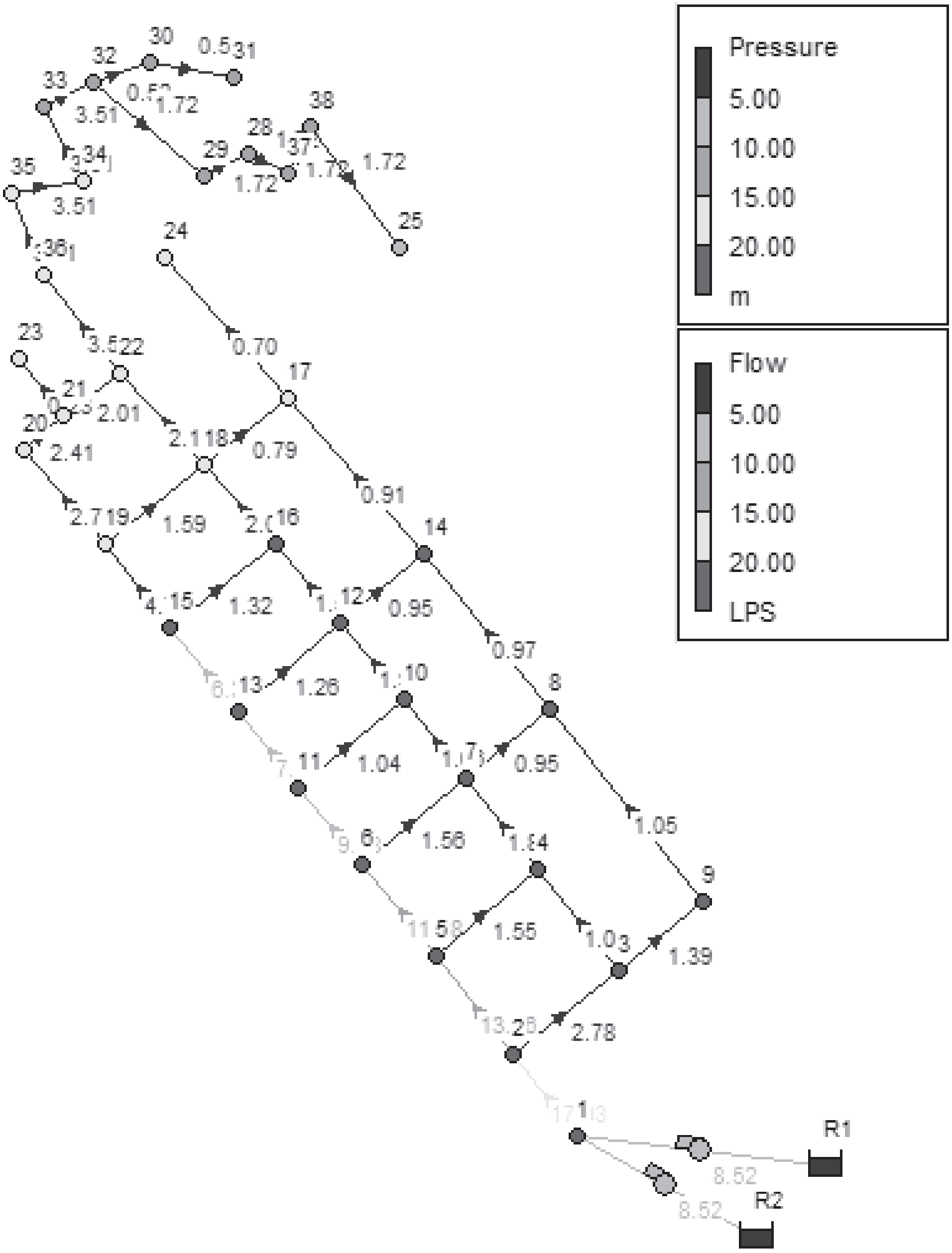

Fig. 1.5. Looped network configuration. Pressure and flow fields at maximal demand hour (7:00 am); constant speed pumps

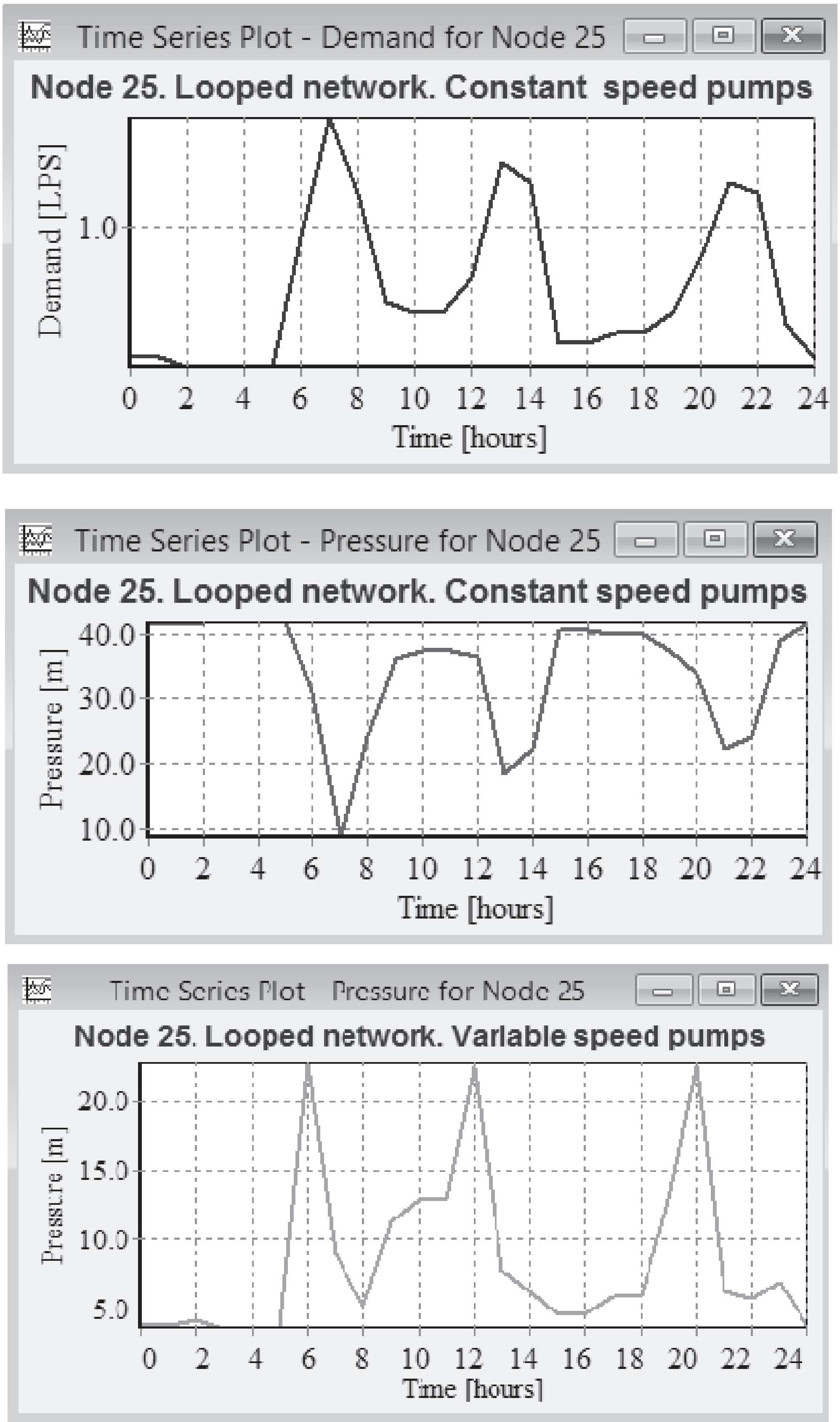

Fig. 1.6. Discharge and pressure variation in node 25 (the furthest consumer)

Pressure variation in node 25 is inversely proportional to the demand, characteristic for constant speed pumps, as it may be seen in Fig.1.6. When variable speed pumps are used, pressure is proportional to the discharge.

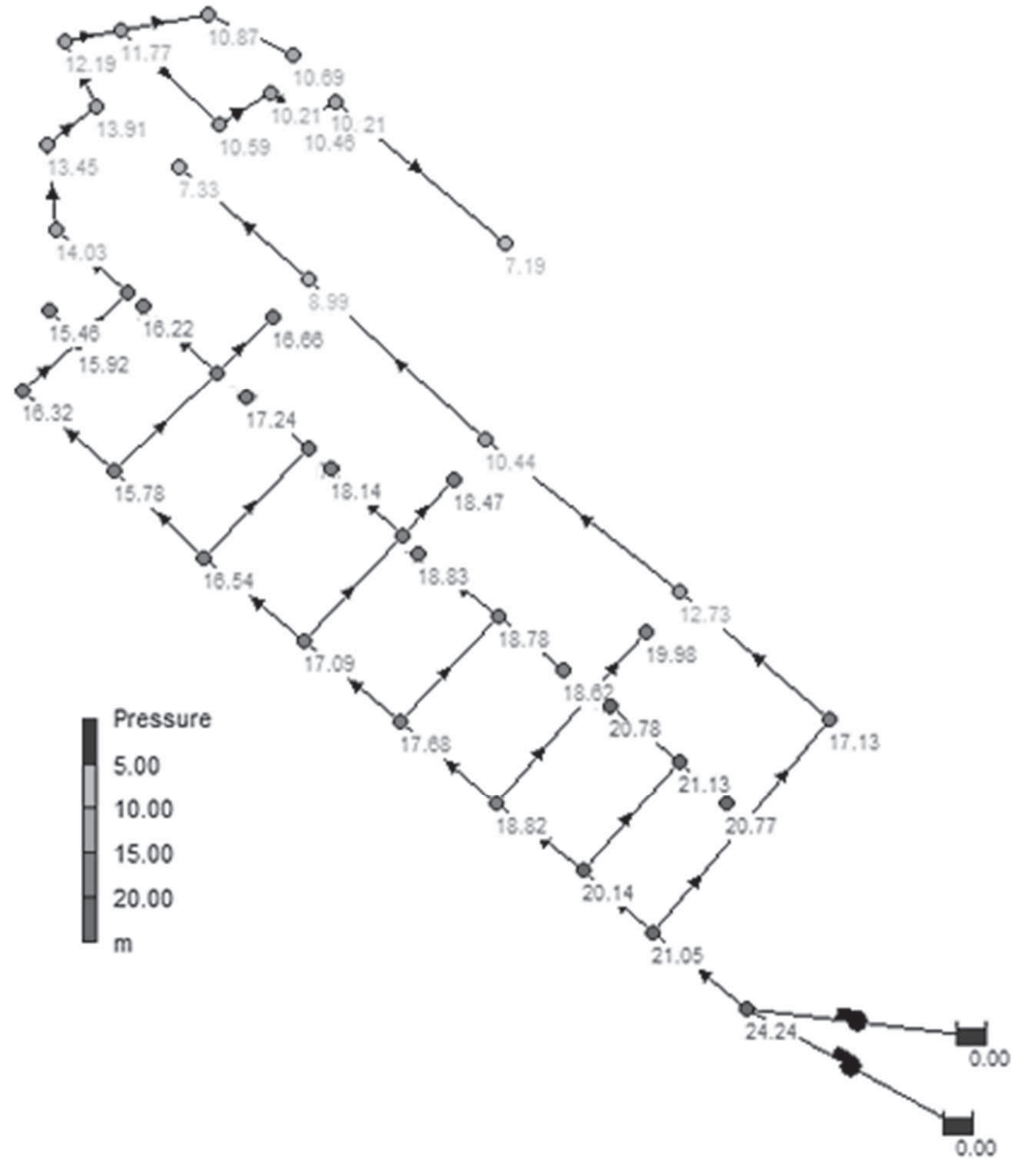

Fig. 1.7. Branched network configuration. Pressure field at maximal demand hour (7:00 am); constant speed pumps

The branched variant, represented in Fig.1.7, has 10 additional junctions compared to the looped one. The hydraulic resistance modulus for the branched network is much smaller $M_b = 60100\ [m^{-5}s^2]$, which allowed us to select a pump model with a smaller head, 23m instead of 29m, at the same discharge.

Consequently the consumed energy decreased, even if the efficiency of the new type of pump is less: only 59.5% instead of 62.4%.

In the case variable speed pumps are used, average pressure decreases and, furthermore, its variation is directly proportional to the demand. In Fig.1.7c it is represented the pressure variation in node 25 for variable speed pumps operating at different speeds, in the proportional way (pressure directly proportional to the discharge). The speed values have been determined by the use of affinity laws. The pressure decreased under the minimal admitted value during night time, therefore, during these intervals the speed had to be increased.

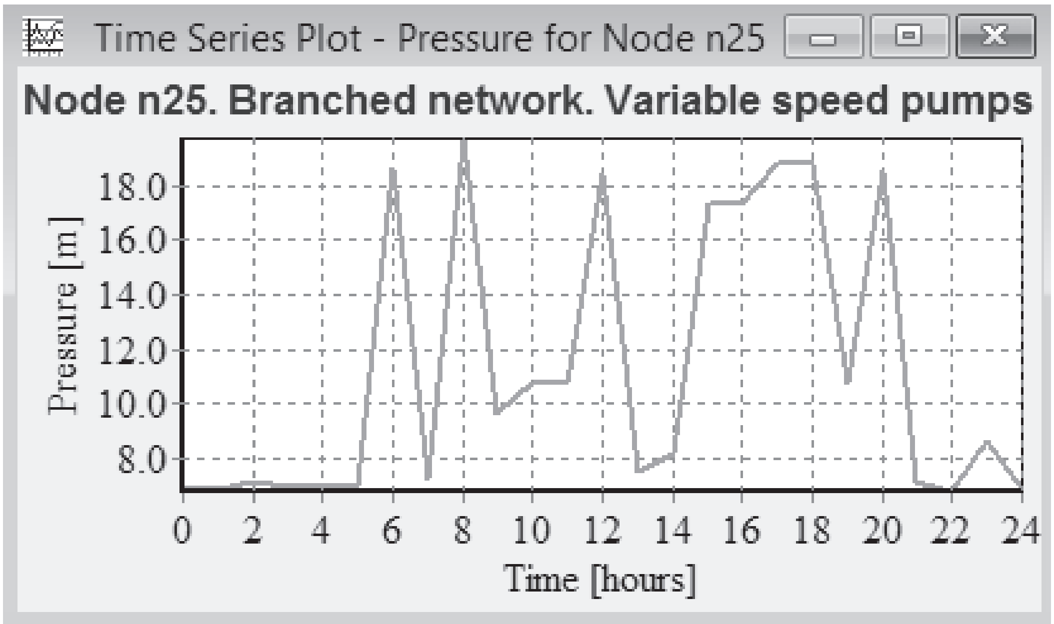

Fig. 1.8. Pressure variation in in node 25. Branched network, variable speed pumps

In Fig.1.8 there is represented the pressure variation in node 25 in the case the lower speed value is limited such way the minimal pressure is kept above 7mwc. The minimal speed is $n_3 = 0.78 \cdot n_{max}$ when both pumps operate. For the low demand values, when only one pump operates, the speed decreases to $n_{min} = 0.40 \cdot n_{max}$.

In EPANET, the controls written to simulate pumps operation takes into account that the number of pumps and their rotation speed vary according to the demand pattern.

Only four of the duty points need both pumps to operate in parallel, as represented in Fig.1.9.

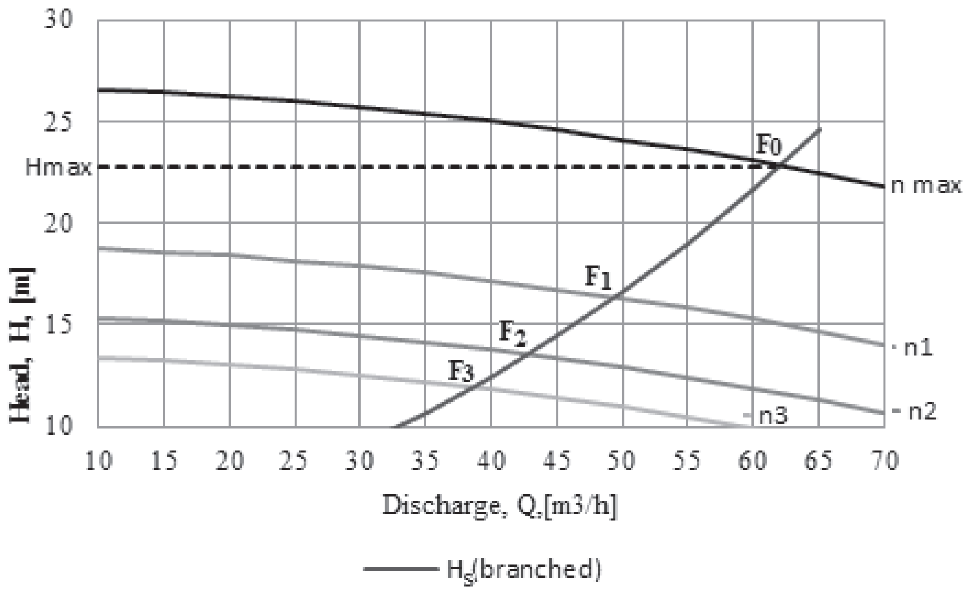

Fig. 1.9. Branched network, variable speed pumps. The duty points where the two pumps operate in parallel

In order to compare the four cases of simulation, the total head values are provided in Table 1.1.

Table. 1.1. Duty points for looped and branched network

Discharge, Q[l/s]												
0.68	1.36	2.21	2.9	4.26	4.94	6.47	7.84	9.2	12.09	12.78	14.14	17.03
Total head, H,[m] Constant speed pumps, looped network												
38.49	38.3	37.9	37.4	36.1	35.3	37.15	36.51	35.7	33.69	33.12	31.9	28.91
Total head, H,[m] Constant speed pumps, branched network												
31.9	31.8	31.4	31.06	30.0	29.35	30.83	30.32	29.7	28.06	27.61	26.63	24.24
Total head, H,[m] Variable speed pumps, looped network												
27.14	26.9	26.6	26.08	24.8	24.61	31.23	30.53	26.4	26.36	28.38	25.98	28.91
Total head, H,[m] Variable speed pumps, branched network												
22.87	22.7	22.4	22.03	21.0	20.84	26.12	25.57	22.2	22.23	23.84	21.92	24.24

The total head in the case of the branched network decreases with about 16%, in comparison with the looped network, considering the variable speed pumps, and the proportional pumping way, where the head is not oversized.

The electric variable frequency drives (VFDs) that supply variable frequency to the electric motor of a hydraulic pump are slightly less efficient than a basic direct on line motor due to additional eddy currents. Other types of VSDs also have additional losses, but these losses are small compared to the overall power saving (Astall 2013).

All the data regarding the energy consumption and average efficiency given by numerical simulation in EPANET are gathered in Table 1.2. According to these figures, the best variant is the branched network supplied by variable speed pumps.

In spite the efficiency decreased in the case of branched network, the specific consumed energy is smaller due to the consistent decrease of the total head.

Best operation point of the pump model used at the looped network is at a higher discharge than the discharge the pump was selected for, so the average efficiency is 62.77%, slightly higher than the pump's efficiency of 62.4%.

Table. 1.2. Energy efficiency for standard water demand during 24 hours and a sizing discharge of 61.3 m3/h

Network type	Pumps in parallel	Pump's parameters		Consumed power [kw]	Specific consumed energy [kwh/m3]	Average efficiency [%]
		Head [m]	Efficiency [%]			
Looped network	Two identical, constant speed pumps	29	62.4	4.56	0.3	62.77
	Two identical, variable speed pumps	29	62.4	2.04	0.15	62.77
Branched network	Two identical, constant speed pumps	23	59.5	3.83	0.26	59.5
	Two identical, variable speed pumps	23	59.5	1.39	0.13	59.5

1.5 Conclusions

EPANET software can process large amounts of data in a short period of time meeting the need of the engineer in charge with the technical design of a water distribution network. By a correct simulation of the network operation in different alternatives of geometry and pumping unit models, this software may be a useful means to obtaining the whole picture of the hydraulic parameters and their evolution in time.

The possibility to investigate different hydraulic system configurations and operation variants offers to the decision makers the basis to select the optimal technical alternative.

The branched configuration of the network proved to be a better solution than the looped one, speaking from the energetic view point. It provides an energy saving of about 0.02-0.03 kwh/m^3. Its disadvantage is the fact that when a pipeline is interrupted by accident all the downstream consumers will have no drinking water.

The network supplied by variable speed pumps is more effective than the variant of constant speed pumps, in terms of energy consumption. They are expensive, therefore a high investment cost is expected, but they can follow a wide variable water demand, characteristic for small water distribution networks, with a consistent power saving. In Smârdan village considering the proportionally pumping method, the energy saving is significant because the static head of the system is small and all the duty points are approximately homologous. In the studied water distribution system, the use of variable speed pumps, operating at proportional pressure, instead of constant speed pumps, led to an energy saving of $0.15\,{}^{kWh}/_{m^3}$ that means a saving of over $50000\,{}^{kWh}/_{year}$. Besides, a decrease of the indirect environmental pollution is also to be expected.

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