Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 119 (2015) 1012 – 1019

Procedia Engineering

www.elsevier.com/locate/procedia

13th Computer Control for Water Industry Conference, CCWI 2015

EPANET simulation of control methods for centrifugal pumps operating under variable system demand

Andrei-Mugur Georgescu[a,*], Sanda-Carmen Georgescu[b], Costin Ioan Cosoiu[a], Liviu Hasegan[a], Anton Anton[a], Diana Maria Bucur[b]

[a]Hydraulics and Environ. Protection Dept, Technical University of Civil Engineering Bucharest, 124 Lacul Tei, Bucharest 020396, Romania
[b]Hydraulics and Hydraulic Machinery Dept, University "Politehnica" of Bucharest, 313 Spl. Independentei, Bucharest 060042, Romania

Abstract

Pump operation control under variable system demand is obtained either by throttling the discharge pipe, by using by-pass pipes, by modifying the rotor speed, or by separating the pump and the demand by means of a pressurized tank. We try to assess the efficiency of pump operation control by using a numerical model created in EPANET for a 24 hours period. To avoid the demand driven algorithm used by EPANET, the network model consists of a throttle control valve followed by an emitter. Pump or valves parameters are modified using control statements. Results are consistent with the general theory.

Peer-review under responsibility of the Scientific Committee of CCWI 2015

Keywords: Variable demand; booster station; variable speed driven pumps; duty operation point; EPANET

1. Introduction

Nowadays, as energy savings and greenhouse gas emission reductions are becoming increasingly important, methods for the efficient control of centrifugal pumps operation under variable system demand have gained momentum. Typically, the control is obtained either by throttling the discharge pipe, by using by-pass pipes and valves, by modifying the rotational speed of the rotor, or, in some cases, by separating the pump and the variable demand by means of a pressurized tank (booster station) [1]. Unfortunately, the efficiency of the control methods is described only in general terms in most hydraulic machinery books, and the extents and limitations of a given

* Corresponding author. Tel.: +4-021-243-3660; fax: +4-021-243-3660.
E-mail address: andrei_georgescu2003@yahoo.com

Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.995

control method are not set clearly [2]. Moreover, the relative lack of information in books about this matter trends to shift students attention from the problem at hand. In this respect, starting from real Romanian design specifications, we devised a numerical model in EPANET that could mimic the functioning of all four control methods for the same network conditions, variable demand and pump characteristic curves. By running one or the other of the four variants (i.e. closing or opening certain pipes of the model and altering control statements), students can try to assess some of the characteristics of pump operation control with respect to the wire to water efficiency of the process, for a 24 hours period.

2. EPANET model

The EPANET model that we used (see Fig. 1) consists of several components that play different roles in the simulations. Those components can basically be divided into two main categories: the variable demand group and the feeder group. The connection between these categories is node 7 (see Fig. 1) that is common to both groups. In the sequel, we will discuss the purpose and the characteristics of each of the two main categories.

2.1. Variable demand group

The variable demand group consists of the throttle control valve (valve 3 in Fig. 1) positioned between node 7 (common to both groups – the control node in all simulations) and the emitter 5.

Emitters are devices associated with nodes that model the flow through a nozzle or orifice. In these situations, the demand (i.e. the flow rate through the emitter) varies in proportion to the pressure at the junction raised to the power 0.5; the constant of proportionality is termed as the "discharge coefficient". Emitters are used to model flow through sprinkler systems and irrigation networks. They can also be used to simulate leakage in a pipe connected to the junction and compute the flow available at some minimum residual pressure. In the latter case, one would use a very high value of the discharge coefficient (e.g. 100 times the maximum flow expected) and modify the junction's elevation to include the equivalent head of the pressure target [3].

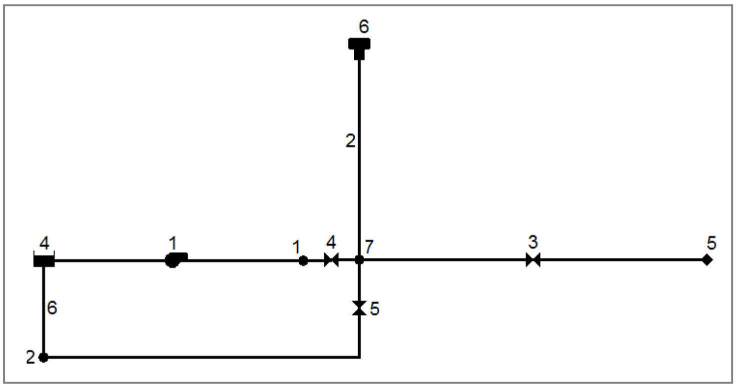

Fig. 1. The EPANET model used in the simulations.

As we use the same network model in all cases, in order to insure the variable demand pattern and avoid the demand driven algorithm used by EPANET, the emitter coefficient was set at a very high value (1000), so that it insures that the flow of water adjusts freely with respect to the available pressure at the emitter. In the same time, the elevation of the emitter was set to include the equivalent head corresponding to a user situated at the 8th floor of a residential building (i.e. 27 m).

A basic model of this group was built separately, in order to assess the values of the minor head loss coefficient of valve 3 necessary at different time steps, so that the discharge trough the emitter matches a 24 hours variation pattern corresponding to the standard water consumption for 1000 inhabitants, while the head of node 7 is kept constant. Node 7 was replaced by a reservoir with the total head matching the value of the constant head that has to be maintained in the node by the control of the pump (i.e. 32 m). As in this basic model the valve could not be connected directly to a reservoir, a small pipe was added between the two (1 m in length, 300 mm diameter and a roughness of 0.1 mm).

The values of the minor head loss coefficient were adjusted manually on the basic model, so that the discharge of the emitter matches all consumption flow rates of the variable 24 hours pattern. Those values were used in the sequel, for all pump control configurations of the complete model, as simple time based control statements of the form "*link 3 16700 at time 5 am*" or "*link 3 9780 at time 7 am*". A total of 17 simple time based control statements were used in the 24 hours simulation.

The obtained values of the discharge trough the emitter are presented in Fig. 2.

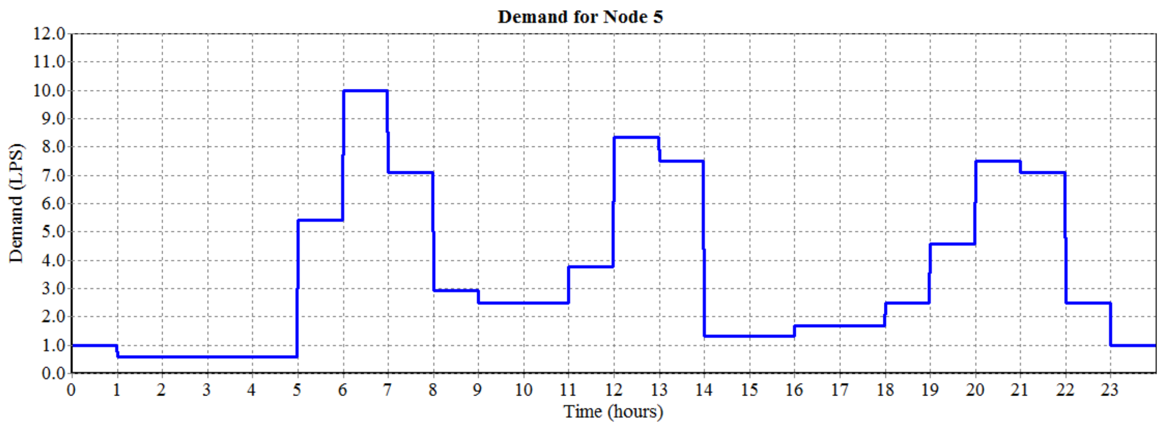

Fig. 2. Values of the discharge at the emitter with a constant head of 32 m at node 7 for a 24 hours period.

2.2. Feeder group

The feeder group mimics pump operation with different control configurations. The components are not used together in the same simulation. For each configuration, some of the components might be closed, while others might be completely opened, so that they pay no role in the simulation. The only components that are used in all simulations are the reservoir 4 and the pump 1 (see Fig. 1). The reservoir has the head fixed at 0 m in all simulations while the pump uses the same head versus flow rate and efficiency versus flow rate curves in all configurations. Pump curves are shown in Fig. 3. The pump was chosen such that, at a head corresponding to 32 m, to be able to deliver the maximum required hourly flow rate from the consumption pattern (10 l/s), with satisfactory efficiency (above 60%).

A pressure reducing valve (PRV) was added after the pump (valve 4 between nodes 1 and 7, in Fig. 1) to simulate the control obtained by throttling the discharge pipe. Its setting was set to 32 (i.e. if enough head is available in node 1 upstream of the valve, the head of node 7 downstream of the valve will be kept at 32 m) and the "fixed status" to "none" in the throttling discharge pipe control simulation. For the other simulations the "fixed status" was set to "opened" so that the control setting of the valve is ignored and the valve behaves as an opened link.

A pressure sustaining valve (PSV) and a small pipe were added between node 7 and the reservoir 4 (valve 5 and pipe 6, in Fig. 1) to simulate the usage of by-pass pipe control of pump functioning. The small pipe is 1 mm long, has a 300 mm diameter and the roughness is set to 0.1 mm. The PSV setting was set to 32 (i.e. the head of node 7 upstream of the valve will be kept at a value of 32 m) and the "fixed status" to "none" in the by-pass pipe control simulation. For the other simulations, both the PSV status and the small pipe status were set to "closed", so that no water passes through the by-pass.

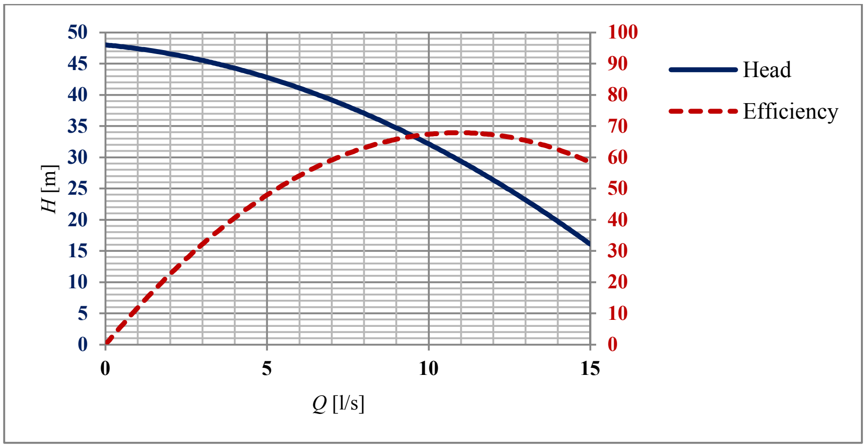

Fig. 3. Pump curves used in all simulations.

No physical components were added to the model for the variable speed control of pump operation. Instead, a set of EPANET rule-based control statements were used to simulate the functioning of the pump at variable speed. The command of the controls is given by the 32 m head in node 7. When diminishing the rotation speed of the pump, the controls are of the form:

"*rule 2*
if node 7 head above 32
and pump 1 setting is 0.82
then pump 1 setting is 0.81"

When increasing the rotation speed of the pump, the controls are of the form:

"*rule 39*
if node 7 head below 32
and pump 1 setting is 0.81
then pump 1 setting is 0.82"

A set of 40 rule-based control statements were used in the variable speed simulation, in order to achieve a rotational speed modification between 100% and 80% of the nominal speed, in discrete steps of 1%. The order in which the rules appear in the program is crucial [4]. At a time step, EPANET computes the hydraulic quantities of the network then, with the results evaluates the conditions from the rules, one after the other, and takes the specified actions if the conditions are met. When all the rules have been evaluated, EPANET passes to the next time step and performs a new hydraulic calculation. Now, it is obvious that, as long as there are no hydraulic calculation after each action, the rules must be specified in a particular order, so that at each time step there is only one rule that meets the conditions necessary to alter the rotational speed of the pump. These rule-based controls were used only for this simulation.

For the booster station model, both physical components and rule-based control statements were added to the model [5]. Pipe 2 and tank 6 are the physical components added to the model. Pipe 2 (between tank 6 and node 7, in Fig. 1) is 1 m long, 300 mm in diameter with the roughness coefficient set to 0.1 mm. Tank 6 is a cylindrical tank with the diameter of 2 m and the elevation set at 31 m. The initial, minimum and maximum levels are set to 0.8 m, 0.7 m and 1.3 m respectively. In other words, for the minimum and maximum levels of the water in the tank, the head at node 7 would be of 31.7 m and 32.3 m respectively.

There are only 2 rule-based control statements for this simulation, one for starting and another one for stopping the pump. The controls are used to maintain the level in the tank between the specified limits, namely:

"*rule 1*
if tank 6 level above 1.2
then pump 1 status is closed
rule 2

if tank 6 level below 0.8
then pump 1 status is open"

These rule-based control statements were used only for this simulation. For the other simulations, the pipe 2 status was set to "closed" so that no water passes through the pipe into or out of the tank 6.

All the nodes that were not mentioned in the above presentation of the model had the elevation set to 0 m. All the simulations use the Darcy-Weisbach formula for friction head loss calculations and the time steps (hydraulic, quality and reporting time step) were set to 1 minute. The energy price per kWh was set to 1 so that the reported daily price would represent the kWh/day consumed by the pump.

3. Results

For the first 2 simulations, that is to say, for the throttle control of the discharge pipe and for the by-pass pipe control, as the elements used in the simulation (PRV and PSV) are built-in EPANET components, the recorded flow rate at the emitter matched exactly the pattern presented in Fig. 2, while the head at node 7 was exactly 32 m for all computed time steps.

For the third simulation, that is to say, for the variable speed control of pump operation, the recorded flow rate at the emitter also matched the pattern presented in Fig. 2. The head at node 7 however was not constant (see Fig. 4).

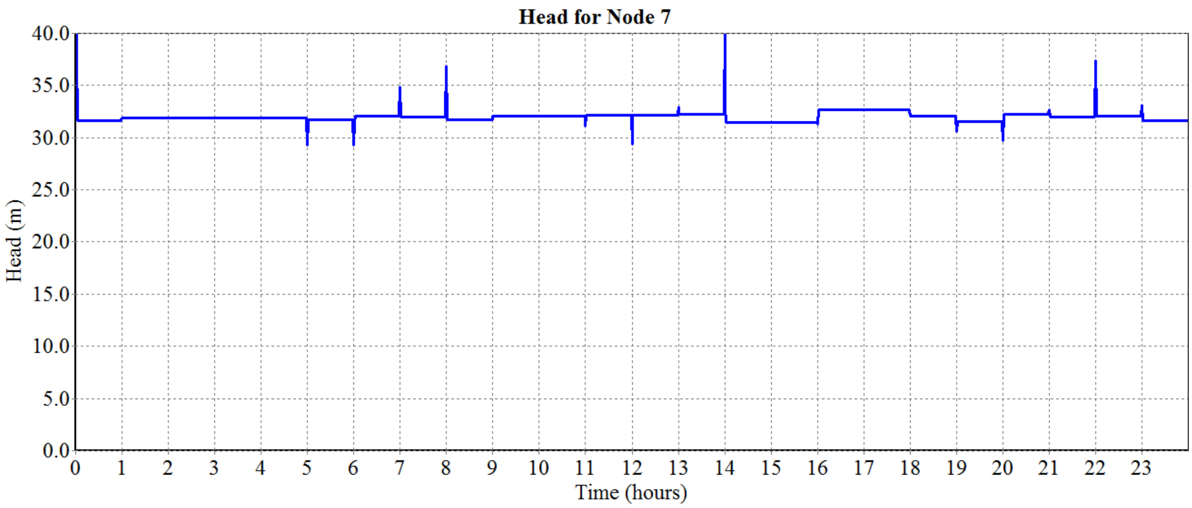

Fig. 4. Values of the head at node 7 for the variable speed control of the pump.

There are two different numerical reasons why Fig. 4 looks like this. The vertical peaks that appear sometimes when the hour of the day changes (i.e. when the demand changes) are due to the previously described algorithm used by EPANET to evaluate the control statements, combined with the rule-based control statements order. In other words, for important values of the differences between the flow rate computed at a time step, and the value of the flow rate that was computed at the previous time step, the necessary variation of pumps speed exceeds 1%, which is the only modification possible at one hydraulic time step, due to the order in which the rule-based controls are written. So, more than one time step is necessary in order to arrive at the correct rotation speed. This is obvious if we compare Fig. 4 with Fig. 2. For each hour where the flow rate increases with an important value with respect to the previous hour (i.e. hours 5, 6, 11, 12, 19 and 20 in Fig. 2), we find a peak below the 32 m prescribed value in Fig. 4. Likewise, when there is an important decrease in flow rate (i.e. hours 7, 8, 14, 22 and 23 in Fig. 2), we find a peak above the 32 m prescribed value in Fig. 4. Moreover, the bigger the difference in flow rates, the more significant are the peaks. The second reason concerns the slight differences of the horizontal segments with respect to the prescribed 32 m head at node 7. This is due to the fact that for some values of the demand (especially for small values) the discrete 1% step for rotation speed modification is too big, so the duty point of the pump cannot insure a head of exactly 32 m at node 7 for the required flow rate. Those differences are however quite small, not exceeding 0.5 m.

For the fourth simulation, that is to say, for the booster station model, neither the recorded flow rate at the emitter, nor the head at node 7 match exactly the requested values. The demand at the emitter and the head at node 7 are presented in Fig. 5.

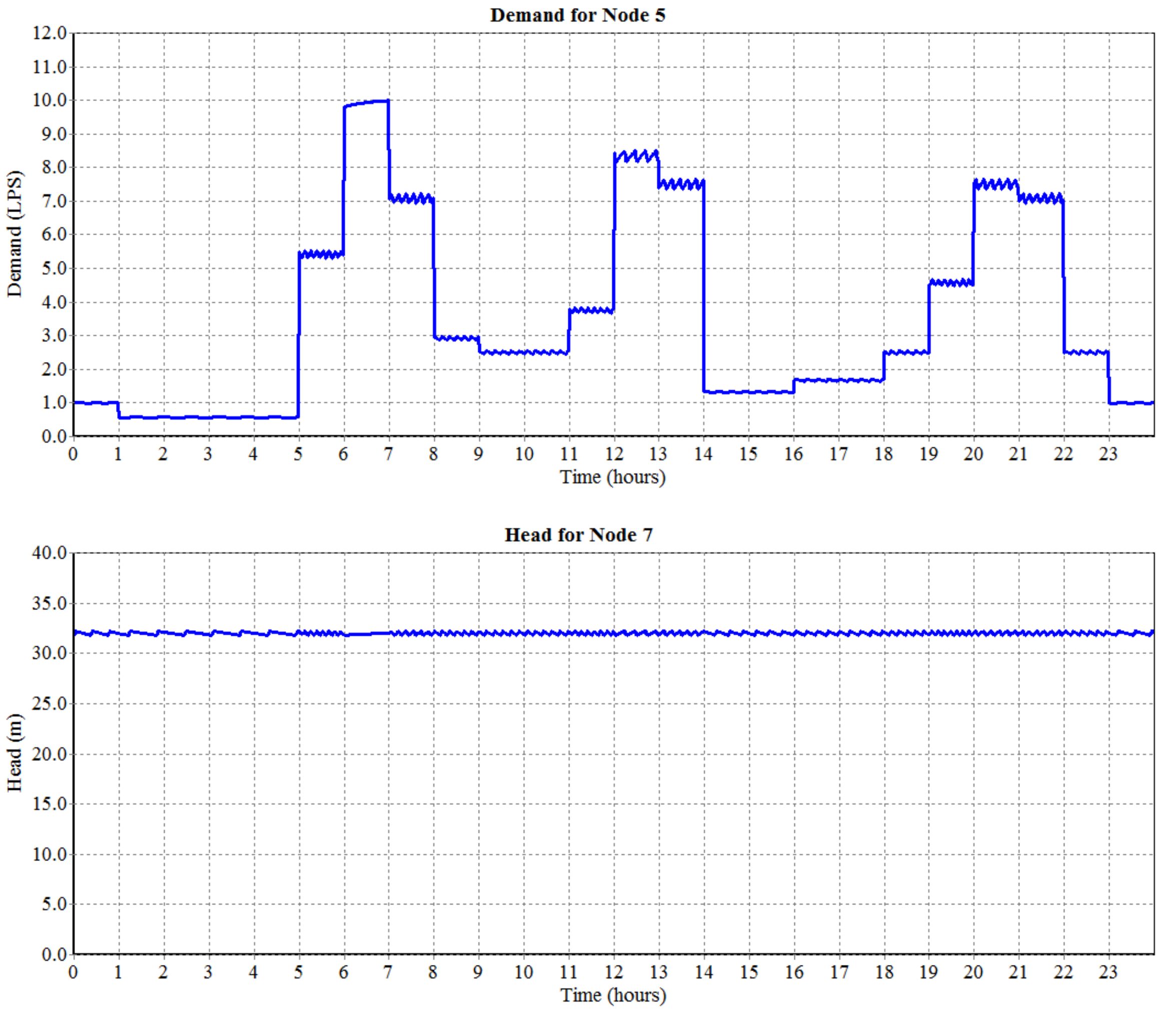

Fig. 5. Variation of the control parameters for the booster station simulation.

In this case, the deviation was expected as long as the implemented control statements allow the level in the pressurized tank (tank 6 in Fig. 1) to vary by 0.2 m with respect to the target value of 32 m.

The recorded hourly energy consumption for the 4 pump control variants is presented in Fig. 6. In order to build up Fig. 6, the data reported by EPANET for the energy consumption every minute (this was the hydraulic time step of the simulations) had to be added for each hour of the day.

From Fig. 6 it is obvious that the booster station control consumes the smallest amount of energy, followed by the variable speed control. The energy consumption of the booster station control is particularly small for hours with small demands, when the pump only starts once or twice an hour. The more energy consuming controls are, in decreasing order, the by-pass valve control and the throttle valve control.

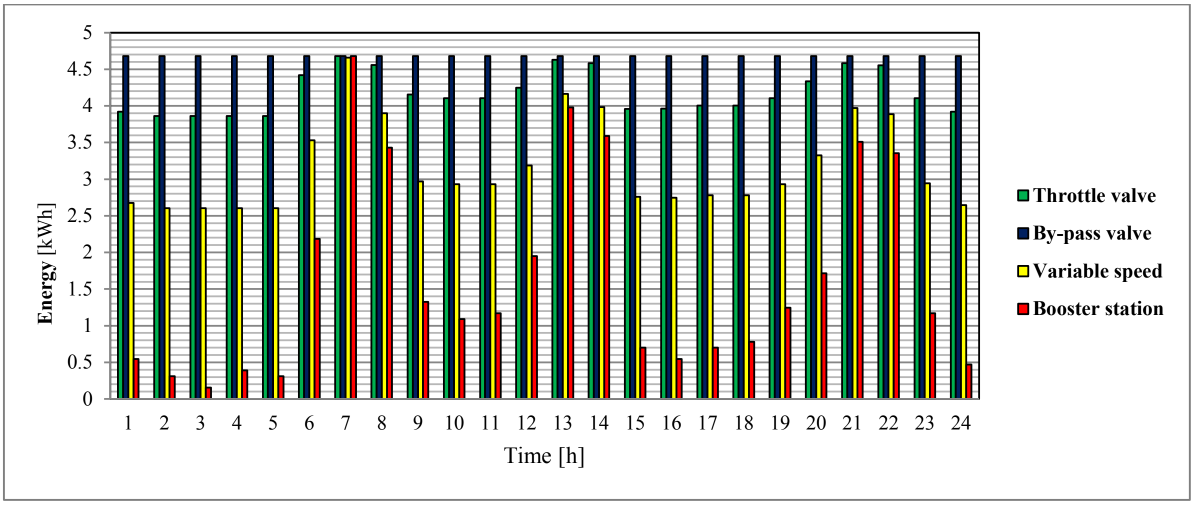

Fig. 6. EPANET recorded hourly energy consumption for the 4 studied control configurations.

Due to the known inability of EPANET to calculate correctly the efficiency of the pump at speeds other than the nominal speed [6,7], starting from the reported pairs of values for the flow rate and head of the pump, we computed with a different software the efficiency of the pump using the affinity laws [8,9] and then the power and the consumed energy. We extended this study for all 4 control variants. Adding the values for the whole simulation, we obtained the per day consumption. Results are presented in Fig. 7.

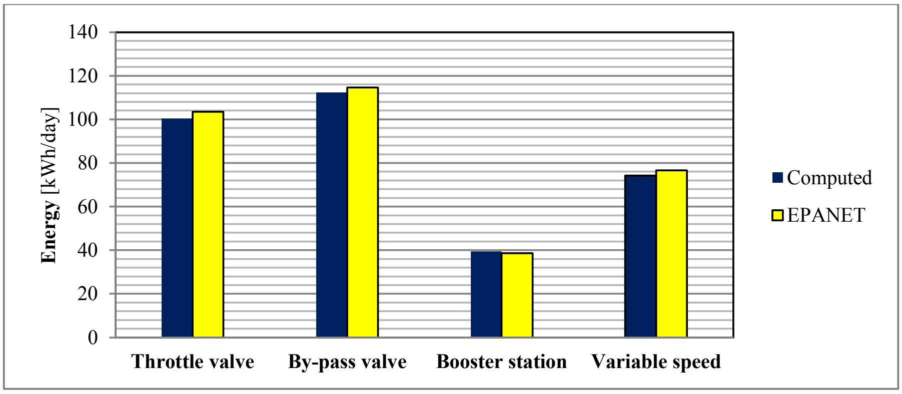

Fig. 7. EPANET reported versus computed daily energy consumption for the 4 studied control configurations.

Surprisingly, the differences between the externally computed values of the energy consumption for the variable speed control and the values reported by EPANET do not exceed the differences that appear for the throttle control or the by-pass pipe control using the same procedure. For the first calculations we performed with the procedure mentioned above, we noticed a huge difference for the booster station control. The calculated values exceeded the values reported by EPANET. This was due to the fact that when a tank is active in a network, EPANET adds additional time steps to the simulation to compute water level in the tank [3]. There is no way to report those additional time steps. To get to the values presented in Fig. 7, we had to change the hydraulic and reporting time steps of the booster station simulation to 10 s. Comparing the two runs of the simulation, it became clear that in the external calculations we have assumed the pump to work the hole time step (i.e. 1 min.), while in the second it only ran for 3 or 4 time steps (i.e. for 30 or 40 seconds). Energy values reported by EPANET for the two runs were almost the same, so we can assume that although EPANET is not reporting the additional time steps, it records the functioning time of the pump correctly. Moreover, as the time step decreases, the externally computed values of the energy consumption tend to approach the values reported by EPANET. The values calculated in Fig. 7 for the booster station control are based on the 10 s time step simulation.

4. Conclusion

The overall conclusion is that the results are consistent with the general theory. We strongly believe that such a model (though academic) can prove useful in the understanding of the different control methods of pumps operating under variable system demand, especially to undergraduate students. The multitude of animations and graphs that EPANET can provide for such simulations adds a real insight to the problem at hand.

Care should however be observed in generalizing the results. They are really valid only for the pump curves and water demand pattern presented in this paper. Further work should include a more thorough study on the influence of the demand pattern and type of pump curves on the results of the analysis.

Acknowledgements

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398.

References

[1] A.-M. Georgescu, S.-C. Georgescu, Pipe networks Hydraulics with EPANET (in Romanian), Printech, Bucharest, 2013.
[2] D. Kaya, E.A. Yagmur, K.S. Yigit, F.C. Kilic, A.S. Eren, C. Celik, Energy efficiency in pumps, Energ. Convers. Manage. 49 (2008) 1662-1673.
[3] L. Rossman, EPANET 2 Users Manual, U.S. Environmental Protection Agency, EPA/600/R-00/057, Cincinnati, OH, 2000.
[4] A.-M. Georgescu, S. Perju, S.-C. Georgescu, A. Anton, Numerical model of a district water distribution system in Bucharest, Procedia Eng. 70 (2014) 707-714.
[5] A.-M. Georgescu, S.-C. Georgescu, Energy consumption quantification for a pumping or booster station using EPANET, in: Proc. 2nd International Conference on Energy and Environment CIEM2005, Universul Energiei Press, Bucharest, 2005, S3_L18.
[6] A. Marchi, A.R. Simpson, Correction of the EPANET inaccuracy in computing the efficiency of variable speed pumps, J. Water Res. Pl-ASCE. 139(4) (2013) 456–459.
[7] A.-M. Georgescu, C.-I. Cosoiu, S. Perju, S.-C. Georgescu, L. Hasegan, A. Anton, Estimation of the efficiency for variable speed pumps in EPANET compared with experimental data, Procedia Eng. 89 (2014) 1404-1411.
[8] A. Marchi, A.R. Simpson, N. Ertugrul, Assessing variable speed pump efficiency in water distribution systems, Drink. Water Eng. Sci. 5 (2012) 15-21.
[9] I. Sârbu, I. Borza, Energetic optimization of water pumping in distribution systems, Periodica Polytechnica Mechanical Engineering. 42(2) (1998) 141-152.