Using MODELICA for calculating the power requirements of a mid-sized city water supply pumping system

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Abstract. The issue of water supply is one of the fundamental issues of the society, it is one of the pillars without which society would not work. The performance of the Targoviste water supply network has fallen over time, so solutions are being sought to optimize this network. A short description of the current situation has been made in the paper and solutions have been proposed for a certain area of capture and pumping of water to consumers. For the choice of pumps, water supply systems, calculations were made for the selection of system pipes, pumping height, pump motor power, and loss coefficients. With the help of the MODELICA calculation program, simulation of the pumping station was carried out using two separate calculation models by means of boundary conditions established with the help of water sources. The simulation of the water supply system was performed to verify that the pump power is sufficient to ensure the flow of water required by the consumer and to determine the operating mode of the drive system (continuous or intermittent).

1. Introduction

The water supply assures the basis for the operation of all social gears, and the water quality issues are a major priority. The control of the flow rate or the pressure of supply systems of water distribution networks is done manually or automated by the use of valves. The maximum efficiency is obtained by operating the pump motors at rated speed and the maximum allowable flow rate.

Although, the use of static converters and variable frequency electric drives is beneficial to pumping systems, more important than variable speed control of pump motors, it is the correct choice of the pumping systems [1].

The continuous increase in the number of connexion, by adding the neighbouring areas of Targoviste to the city network, and increasing the active population, basically doubling the population served in the last 40 years [2], led to the pressure reduction to values below 1 bar in certain areas of the network supply.

2. The performances of the pumping station. The current situation.

The pumping station construction should meet the need of water supply to the new policy of sustainable development at the same time [3].

The City Drinking Water Transport and Distribution Network of Targoviste has a total length of 140 km, of which 39.6 km were recently rehabilitated: 19.2 km from network for supplementing
networks that no longer meet the consumption increase and 20.4 km from network for replacement of very old networks.

Targoviste water supply system was designed and executed in an annular system (Figure 1), having diameters between 100 - 600 mm (Table 1).

Table 1. The dimensions of the water network pipe-lines depending on the diameter

| Diameter (mm) | Length (km) |
|---------------|-------------|
| 50            | 16.5        |
| 80            | 14          |
| 100           | 38.5        |
| 150           | 29          |
| 200           | 14.5        |
| 225           | 5           |
| 250           | 3.5         |
| 300           | 1.5         |
| 400           | 9.5         |
| 600           | 8           |

To make the pumping system more efficient, the water networks have been connected and pressurized to two pressure levels, namely:
- low pressure network, which is realized annularly, supplies 35 pressure raising stations that fuel the buildings in Targoviste Municipality, private houses and the buildings of companies, in permanent regime, and 8 pressure raising stations for the neighbouring communes.
- high pressure network, not-interconnected, which supplies groups of housing blocks, public institutions, economic agents.

Figure 1. The network of distribution of Targoviste City, the points of pressure and the water flow rate at the network entrance, according to the measured data at the control panel of central dispatching of Water Company Targoviste, Dambovita.
The stations of pressure raising have 4 pumps each, one operated at variable speed, variable revolution speed, controlled by a speed variation, to maintain the constant pressure in the system under the conditions of variable consumption. The groups of pumping from hydrophore stations are HMLV 50.2x5 with \( Q=80 \text{ m}^3/\text{h} \), HMLV 65x4 with \( Q= 100 \text{ m}^3/\text{h} \), and respectively HMLV 80x4 with \( Q= 180 \text{ m}^3/\text{h} \).

2.1. Dragomiresti North Water Capture Front

Dragomiresti North water capture front is monitored and is located to approximate 10 km from Targoviste, it contains 22 wells with drilling depths between 12 ... 60 m and they are equipped with Grundfos submersible electropumps of types SP46-4 7.5 kW, SP16-5 3 kW and steel pipes \( D_n = 100 \text{ mm} \). The distance between drillings is 120 m. The captured water is transported towards Dragomiresti station tank of 1250 m\(^3\) through 2 telescopic metallic pipes \( D_n =100 \text{ mm} \) respectively \( D_n =300 \text{ mm} \), these pipes are connected to a metallic pipe \( D_n =500 \text{ mm} \), with the length of 500 m. The total length of the water capture front is 3600 m.

![Figure 2. Dragomiresti North pumping station with the drilling wells, the storage tanks of the water and the horizontal submersible centrifugal pumps. Only two drilling wells are in the Figure.](image)

Dragomiresti North pumping station still has a water capture front in the perimeter formed by 6 drillings, of which only 4 are functioning now. These drillings are equipped with prefabricated tubes of \( D_n = 100 \text{ mm} \). The drillings have depths of 10-12 m, except the drilling 5 which was been reactivated again to depth 64 m. This drilling is equipped with a Grundfos submersible electropump of type SP46-4 7.5kW and a steel pipe \( D_n =100 \text{ mm} \) and the length 30-35 m. The drilling 2, 4 and 6 are equipped with the Grundfos submersible electropump of type SP27-3, 3kW. The distance among drillings is between 150...200 m. The total length for this is 1000 m.

The operating flow rate of Dragomiresti North water capture front is 170 l/s. The water accumulated into the tank 1250 m\(^3\) is pumped towards the storage tanks from Priseaca by a steel and PREMO pipe \( D_n = 600 \text{ mm} \), by means of a pumping station equipped with 5 horizontal electropumps of centrifugal type CM250x150x400 (Figure 2).
3. The choice of pumps, the water supply systems
The preliminary choice of the centrifugal pump and the water pipes will be made for a capture well of the pumping station of Dragomiresti North. As hypothesis of calculus is considered that the pumping system used a horizontal centrifugal pump, the water level into tank is kept constant to a level of 6 m, the capture tank (the case considered) has a depth of 60 m. The water level into the capture tank is imposed to 30 m and the imposed water flow rate at the exit is 45 m³/h. The length of the intake pipe is 100 m, and the length of discharge pipe is 1000 m.

![Diagram of the water pumping system](image)

Figure 3. The water pumping system dimensioned for a well of Dragomiresti North station – when a horizontal centrifugal pump is used

3.1. Choosing the diameter of the intake and discharge pipes
The diameter of the intake and discharge pipes is determined by imposing the speed of flows of water into pipes: \( v = 1...2 \) m/s by the intake pipe and respectively \( v = 2...3 \) m/s by discharge pipe. For the flow rate 45 m³/h is chosen a diameter of intake pipe \( d_{\text{int}} = 101.16 \) mm and a diameter of discharge pipe \( d_{\text{desc}} = 76.2 \) mm.

3.2. The calculus of the pumping height
The total pumping height is calculated following the relation:

\[
H_{\text{tot}} = H_s + \left( K_{\text{fit}} + K_{\text{cond}} \right) \frac{v^2}{2g} = H_s + \left( K_{\text{fit}} \cdot \frac{v^2}{2g} + h_f \right) = 36m + 92m = 128m
\]

where, the static height is \( H_s = 36 \) m, according to Figure 3. The difference of height, because the neglect of differences of pressure among the tanks and the difference due to the pressures of speed at pump, is \( \Delta H = 0 \). The calculus of the dynamical height depends of losses, meaning by the speed of the flow into pipe and the coefficients of losses \( K_{\text{fit}} \) and \( K_{\text{cond}} \).

| The way of flowing | Valve | Elbow | Tank | Directional valve |
|--------------------|-------|-------|------|-------------------|
| Intake pipe        | 2×0.16| -     | 0.5  | -                 |
| Discharge pipe     | 2×0.25| 3×0.35| -    | 1×2               |
Table 3. The height of losses by friction in pipes

| The way of flowing | d | $h_f$ | $\frac{v^2}{(2g)}$ |
|-------------------|---|-------|------------------|
| Intake pipe       | 3 | 2.27  | 0.395            |
| Discharge pipe    | 4 | 8.9   | 1.17             |

3.3. The power of the pump’s motor

The preliminary calculation imposes a motor of pump with the power:

$$P = \frac{Q \cdot H \cdot g \cdot \rho}{\eta} = \frac{0.0125 \cdot 128 \cdot 9.81 \cdot 1000}{0.7} = 22.5 \text{ kW}$$

(2)

where, for the efficiency of pump and motor, we choose $\eta = 70\%$. The optimization of pumping system is made by the calculus of the pump’s power for several values of the diameter of pipes. So, the reducing pump power and the pumping cost can be done by the reducing power losses in the discharge pipe. If considering a discharge pipe with the diameter 4 inch, and we repeat the calculation process, we obtain total height of pumping 63 m and a pump with the power 10.7 kW, for an impose efficiency at 70%.

3.4. The coefficient of losses

The coefficient of losses is calculating $K_{cond}$, power pump’s motor is calculating, the values obtained by calculation are shown in Table 4. The roughness coefficient of the pipe was chosen for a 0.025 mm steel pipe [4]. The height of pressure losses was calculated quite accurately to 61 m, instead of 63 m. The motor power is estimated at about 10.7 kW in both cases.

Table 4. Results of the pumping height calculation

| Sizes                              | Symbol   | Values   | Measurement unit |
|------------------------------------|----------|----------|------------------|
| Diameter of intake pipe            | $d_{abs}$| 0.1016   | m                |
| Section intake pipe                | $A_{abs}$| 0.00810732 | m$^2$            |
| Speed into intake pipe             | $v_{abs}$| 1.541816595 | m/s             |
| The roughness coefficient          | -        | 2.50E-05 | m                |
| Dynamical viscosity of water       | $\nu$    | 1.31E-06 | kg/s·m           |
| Reynold Number                     | Re       | 119579.058 | -                |
| The coefficient of friction        | $f$      | 0.018708461 | -               |
| The coefficient of losses due to fittings | $K_{fit}$| 1.26   | -                |
| The coefficient of losses due to pipe | $K_{cond}$| 202.55 | -                |
| Dynamically height                 | $H_D$    | 24.69    | m                |
| Statically height                  | $H_S$    | 36       | m                |
| Total height of pumping            | $H$      | 60.69    | m                |
| Power of motor                     | $P$      | 10632.3  | W                |
3.5. Choosing the pump using the manufacturer's calculation tools

![Figure 4. The characteristics $H = f(Q)$ and efficiency of pump, and the characteristics pump's motor CR45-4 15 kW](image)

Water pumps allows for transfer of water to a higher height or a determined length [5].

Pump choice can be made directly from the catalogue using computational tools manufacturer. Example, according to Grundfos [6], imposing a minimum flow 45 m$^3$/h, it results that the pump CR45–4, 160MD 15 kW with the characteristics from Figure 4 can be used for the previous pumping system. In this case, the water flow into pipe will be 48.5 m$^3$/h. The power of motor will be 13.4 kW. Checks on this choice are still needed.

3.5.1. The cavitation and NPSH. The NSPH available from the system should be design than the NSPH required by the pump. The consideration of the NSPH value during the design stage will enhance the reduction for cavitation to occur [5].

The relation of calculation is:

$$NPSH = p \pm H_s - H_f - H_{vp}$$  \hspace{1cm} (3)

where $p$ is absolute pressure at surface of fluid in the intake tank, $H_s$ is distance between the surface of fluid and the centre of impeller, $H_f$ is the height of losses by friction in the intake line, $H_{vp}$ is the vapor pressure of the liquid at the pumping temperature, expressed in m.

For the example shown above calculation (the pump CR45-4 15 kW operating at a flow rate of 45 m$^3$/h) the allowable value $NPSH_{adm} = 2.88$ m is extracted from the manufacturer's diagram. The net positive absorption height is:

$$NPSH = 10.2 \text{ m} - 30 \text{ m} - 2.36 \text{ m} - 0.23 \text{ m} \ll NPSH_{adm} = 2.88 \text{m}$$  \hspace{1cm} (4)

The chosen pump CR45-4 cannot be used due to the cavitation phenomenon. For the previous system, the hypothesis of using a horizontal centrifugal pump at 30 m above the surface of the liquid was considered.

| Table 5. Necessary data for calculation of the value NPSH for prediction of the cavitation of the pump |
| Absolute pressure | $1 \text{atm} \Leftrightarrow 10.2 \text{m}$ |
| Absorption height  | 30 m |
| Liquid             | apa: 20$^\circ$C |
| Height of friction on absorption pipe | 2.36 m |
| Vaporization pressure | $0.023 \text{atm} \Leftrightarrow 0.23 \text{m}$ |
A centrifugal pump can be used, if it is positioned below the ground level, and for safety reasons in service, in this case it must be installed below the water surface level in the capture tank to minimum 10 m deep. In many cases, the technical solution, does not allow this, because a room for pumps in the basement pumping stations does not exist [7].

![Figure 5. Power characteristics and NSPH characteristic of the pump CR45-4 15 kW](image)

The diagram of pumping from Figure 3 is modified by used a submersible pump SP46-8. The characteristic $H=f(Q)$ of the pump are shown in Figure 6. If eliminated the valves from the way of absorption, the losses by friction are reduce. The losses on the way of discharge increase due to increase the length of the pipe of discharge. The net positive height is recalculating:

$$NPSH = 10.2 \text{ m} + 30 \text{ m} - 2.36 \text{ m} - 0.23 \text{ m} >> NPSH_{adm} = 3.49 \text{ m}$$

(5)

The pump SP46-8 can be used. A pump of about 15 kW can be rise water in a well of capture with deep 60 m and it can be transporting water with flow rate of 45 m$^3$/h to 1000 m of the capture tank.

![Figure 6. The characteristics of the pump SP46-8 7.5 kW, used to rise water in Dragomiresti North pumping station](image)

To reduce the loss, a pipe with a minimum diameter of 4 inches should be used on the discharge path. The use of 7.5 kW pumps involves halving the flow rate or increasing the diameter of the discharge pipe, long enough to reduce the losses by more than 75% in pipe.

The water pumps SP46-8 used at Dragomiresti North work at about 50% the maximum efficiency. A possibility to increase pump efficiency would be to choose 15kW pumps that work alternately depending on the needs of the consumer.
The pumps of type SP17-5 (3kW) were installed in wells with deep of maximum 10 m, what makes for a total height of pumping of approximately 45 m it to operate a flow rate of approximately 14 m³/h = 3.9 l/s with the maximum efficiency (70%). However, the 3 kW pumps cover only a requirement of 13x3.9 l / s = 50.7 l / s of the total 170 l / s, i.e. 30% of the total. Nearly 70% of water requirements is covered by other pumping systems, which require improvements, either by the change pumps’ power, either by building some semi-buried tanks near the pumps of 7.5 kW. From the calculations, it results that the 7.5 kW submersible pumps have been placed at a depth of no more than 10 m from the water level, which makes their use possible only when the capture wells are filled with water, the variation margin of the water level not exceeding 6 m.

4. **The simplified model of Dragomiresti North water pumping station used MODELICA**
The Modelica.Fluid library includes the interface and basic components for object-oriented modelling of the convective flow of a fluid into a network containing reservoirs, pipes, pumps, fittings and valves. All components are implemented in such a way that they can be used for different environments [8]. The calculation hypotheses can be entered into an external object called a system. All assumptions can be redefined locally for each component [9], [10].

The simulation of the pumping station is carried out using two separate calculation models by means of boundary conditions established with the help of the water sources (Dragomiresti North capture tanks and Priseaca storage tank) and respectively the discharge valves on the consumers supply way. The separation of the system in two models makes possible, first the determination of necessary mechanical power of the pump to provide water with the imposed flow rate and to calculate the connexion times of pumps for to ensure the necessary water flow rate, and secondly, ensuring the stability of the simulation programs.

“Dragomiresti North 1” simulation program (Figure 7) includes the model of the water pumps, pipes connections between pumps and tank, and the automatic controllers by maintaining the pressure within the limits imposed of the height of the water level from capture tanks.

“Dragomiresti North 2” simulation program (Figure 8) includes the model with 5 water pumps, which are connected between the water tank from Dragomiresti (the first water tank of the network) and the storage tank of water from Priseaca (the second water tank of the network), the model with the water pipes and valve output to consumer (the city water network - entrance from Priseaca).

![Figure 7. "Dragomiresti Nord 1" simulation model for Dragomiresti Nord pumping station (capture).](image-url)
In Figure 7, “Pumps” is the model with 13 pumps of 3 kW which are connected in parallel, and “Pumps2” is the model with 14 pumps of 7.5 kW, which are connected in parallel, which are simultaneously controlled: on/off. The consumer is simulated using the valve “userValve”.

In Figure 8 “Pumps” is 5 horizontal centrifugal pumps of 55 kW, which are connected in parallel, they pump the water from the Dragomiresti storage tank to Priseaca storage tank. The water flows from Priseaca tank towards the city network is modelled by imposing an output pressure of 1.23 atm at the border (sink).

4.1. Pumping station functioning description
The water flows to the consumer at an imposed flow rate through an output valve (userValve, Figure 7 & Figure 8). The pressure drop on the valve is set in the program to consider the losses of pressure in the passive circuits (fittings, elbows, junctions). The water storage tank (source) supplies necessary water to the consumer. When the valve is open, the water level begins to drop in tank. Because the water flow rate at consumer needs to be maintained within certain limits, there is realised an automatic control of the water level from the storage tank by means of pressure controller (controller), a pressure sensor is connected to the output of the water tank. Pressure control is performed by comparing the pressure measured by the sensor with a reference pressure, and when the difference between the required size and the measured value is detected, a control signal is transmitted to the pumps.

A PI-type regulator is used to linearize the control signal and to avoid possible control problems in the control and control circuit, it delays the signal with a time constant of a few seconds (2 seconds in this case). The pumps are commanded to start with a 6 second imposed speed ramp to reach speed from 0 at rated speed (3000 rpm for low power pumps and 1500 rpm for high power pumps). To stop, the same 6-second ramp is required.

4.2. The simulation results
The simulation of the water supply system was performed to verify that the pumps power is sufficient to ensure the flow rate of water demanded by the consumer and to determine the type of operation of the drive system (continuous or intermittent). Figure 9 shows the calculated power characteristics of the pumps. For the calculation of the power absorbed by the motor the efficiency is considered $\eta = 0.7$, resulting in the pump motor power of $P_1 = 2.6 \text{ kW} / 0.7 = 3.7 \text{ kW}$ and $P_2 = 5.2 \text{ kW} / 0.7 = 7.4 \text{ kW}$. In this case, the service of operating is intermittent and permissible operating power is generally higher (in this case 10%, i.e $\sqrt{\frac{800}{650}} \approx 1.1$) than the rated power. It is noted that the installed power of
7.5 kW (pump SP46-4) and 3 kW respectively (pump SP17-5) covers the required power requested by the pumps to ensure a flow rate of 200 l/s. The imposed water flow rate is 170 l/s.

The improvement of the pumping system includes the successive start of the pumps using one or more inverters. After starting a pump and reaching the rated speed, the inverter is disconnected from the pump motor and connected to the motor of another pump, which is switched off and ready for starting. Once the pump runs at rated speed with the motor powered at rated voltage, it can be connected directly to the power supply.

The water level in the Dragomiresti Nord water storage basin is shown, Figure 11 shows the variation of the water flow rate to the consumer, Figure 12 shows the relative control pressure of the automatic regulation system.

![Figure 9. Calculated power of pumps SP46 / 4 and SP 17/5](image)

![Figure 10. Water level in Dragomiresti Nord water storage tank](image)

![Figure 11. The water flow rate to consumer (water tank from Priseaca)](image)

![Figure 12. The relative pressure measured in the water tank (Dragomiresti Nord)](image)
The simulation program no. 2 (Figure 8) is similar to the model shown in the simulation program no. 1.

The water flows from the Priseaca basin to Targoviste distribution network under the influence of gravitational force at a constant flow rate (Figure 13). The water level in the basin is maintained at a relatively constant value (Figure 14) by turning on and off the 5 horizontal centrifugal pumps. The adjustment of the starting and stopping of the pumps is done by imposing a relative pressure reference value of 0.4 bar with a control band of 0.02 bar (Figure 15). In the simulation program, all 5 pumps are switched on and off simultaneously. The maximum power absorbed by the single-pump motor is, according to the simulation results, of \( P_1 \approx 50 \text{ kW}/0.7 = 71.4 \text{ kW} \). The intermittent power is about 80% higher than the rated power in continuous operation \( P_N = 55 \text{ kW} \), assuming the effective power [11] valid rule, i.e. \( \sqrt{\frac{430}{135}} \approx 1.8 \).

![Figure 13. The calculated water flow rate on the city's water supply pipe from the Priseaca storage basin by imposing a pressure 1.23 atm to entry in network](image)

![Figure 14. The calculated water level in Priseaca storage basin](image)

![Figure 15. The relative pressure in the Priseaca storage basin](image)
Figure 16. The power of a pump used for watering the Priseaca storage basin

5. Conclusions
The total installed power of the water supply pumps of the Priseaca storage basin is sufficient if the flow rate of water at the entrance to the city network does not exceed 0.32 m$^3$/s equivalent to 1152 m$^3$/h. Figure 1 shows the measured value at the entrance from Priseaca to the city's water supply network of 1100 m$^3$/h. This value is not enough to ensure a constant pressure of more than 1.2 bar at all points of the city network, with values below 1 bar being observed at certain points of the network. Therefore, to improve the water supply of the city, as the Priseaca entry, the installed power needs to increase simultaneously with the efficiency of the operation of the Dragomiresti Nord submersible pumps, which feed the storage tanks from Dragomiresti Nord and Priseaca. A disadvantage of the pumping system is the large distance between the capture front and Dragomiresti Nord water storage tank. Possible water improvement may not only be an investment in increasing the pump power but also the possible construction of small storage tanks near the wells to allow submersible power pumps, such as 7.5 kW pumps greater depths.

The correct choice of pumps is more important than the potential control of pumps to reduce energy consumption. Because the northern area of the city necessitates an urgent improvement of the power system, the case of the Dragomiresti Nord pumping station and the operation of the water supply system in Priseaca water tanks has been treated as an example. Based on the available data, it was found that the 3 kW water pumps used in the water wells in the Dragomiresti Nord capture front were correctly selected.

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