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ENERGY RECOVERY POTENTIAL FROM EXCESS PRESSURE in WATER SUPPLY and DISTRIBUTION SYSTEMS

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Abstract

Sustainability of water supply systems has started to become an important issue besides continuous and hygienic supply of water. Sustainable water supply systems require improvement of energy efficiency, reduction of energy and water losses in water distribution systems and reduction of carbon dioxide emissions. Pressure is one of the main design parameters for gravity water supply systems and water distribution networks. Therefore, pressure has to be between certain limits. An excess pressure occurs during water transmission from high elevations of water resources to low elevations. By use of break pressure tanks, water storage tanks or pressure reducing valves (PRV) excess pressure is reduced and damages on transmission pipes are prevented. However, energy recovery from excess pressure is possible at this stage by using turbines. Similarly, PRVs are used at certain locations of water distribution networks to control excess water pressure and to reduce it down to optimum operational levels. Energy recovery from excess pressure is also possible at this stage although energy recovery will be low. High pressure at water supply systems causes both energy and water losses. In Turkey, allowable water pressure at water distribution networks is between 20-60 m water column but excess pressure is commonly observed. At low pressure levels, water cannot reach water subscribers and this causes customer dissatisfaction. On the other side, at high pressure levels, water losses and pipe bursts increase which causes indirect increase in energy losses. For sustainable operation of water distribution networks, it is recommended to divide the network into smaller and independent subzones (District Metered Area, DMA). By placing a flow meter and a pressure meter at the entrance of a DMA, flow rate and pressure could be monitored on-line. However, in order to monitor spatial and temporal variations of flow rate and pressure at all pipes in the network, a hydraulic model is necessary. By using a hydraulic model, optimum operational pressure at each DMA of a network could be defined and excess pressure areas could be determined. Afterwards, suitable locations for energy recovery in the network can be estimated. In this study, existing applications for energy recovery from gravity water supply systems and water distribution networks are presented. Additionally, a pilot application of a Pump As Turbine in Antalya water distribution network is described for energy recovery form excess pressure.
Keywords: drinking water supply, renewable energy, turbine, breaking excess water pressure

İÇMESUYU İLETİM VE DAĞITIM SİSTEMLERİNDE FAZLA BASINÇTAN ENERJİ ÜRETİM POTANSİYELİ

Özet

İçmesuyu temini sistemlerinin sağlık ve hijyen koşullarına uygun şekilde ve kesintisiz olarak iletiminin yanı sıra sürdürülebilir özellikte olması büyük önem kazanmaktadır. Sürdürülebilir içmesuyu temini sistemi için enerji verimliliğinin geliştirilmesi, şebekedeki enerji ve su kayıpları ile birlikte karbon dioksit emisyonlarının azaltılması gereklidir. Cazibeli içmesuyu iletim hatları ve dağıtım şebekelerinde temel tasarım parametrelerinden birisi basınçtır ve basıncın belirli limitler arasında tutulması zorunludur. Yüksek kotlarda yer alan su kaynaklarından düşük kotlara suyun iletimi sırasında borulardaki fazla su basıncının azaltılması gerekmektedir. Bu amaçla kullanılan maslak, hazne veya basınç düşürme vanaları (Pressure Reducing Valve, PRV) ile fazla basınç düşürülerek fazla basıncın iletim hattı borularına vereceği zararlar engellenmektedir. Ancak, bu süreçte türbin kullanılarak fazla basınçtan enerji kazanımı mümkündür. Benzer şekilde içmesuyu dağıtım şebekelerinde de yüksek basınç seviyelerinin kontrol altına alınabilmesi için belirli noktalarda PRV kullanılarak, şebeke basıncı, optimum işletim basıncına indirilmektedir. Bu süreçte de fazla basınçtan enerji kazanımı az miktarda olsa bile mümkündür. Su temini sistemlerindeki yüksek basınç hem enerji, hem de su kayıplarına neden olmaktadır. Türkiye'de içmesuyu dağıtım şebekelerinde izin verilen su basıncı 20-60 mss aralığında olmakla birlikte şebekelerde genellikle yüksek basınç değerleri gözlenmektedir. Düşük basınç değerlerinde şebeke suyu abonelere ulaşamadığından, müşteri memnuniyetsizliği yaşanmaktadır. Diğer yandan yüksek basınç değerlerinde ise şebekedeki su kayıpları ve arıza sıklığı artmakta, dolaylı olarak enerji kayıpları da yükselmektedir. Su dağıtım şebekelerinin sürdürülebilir işletimi açısından, şebekelerin kontrolü kolay olan daha küçük boyutlu bağımsız alt bölgelere ayrılması (District Metered Area, DMA) önerilmektedir. Alt bölgelerin girişine yerleştirilen debimetre ve basınç metreler ile alt bölgelere verilen toplam debi ve basınç değerleri anlık olarak izlenebilir. Ancak şebekenin tüm borularındaki debi ve basınç değerlerinin alansal ve zamansal değişimlerinin tahmini amacıyla hidrolik modellerin kullanımı gerekmektedir. Hidrolik model ile optimum şebeke işletim basıncı ve şebeke içerisinde enerji kazanımı açısından uygun lokasyonlar tanımlanabilir. Bu çalışmada içmesuyu temin sistemlerindeki fazla basınçtan enerji üretim potansiyeli için mevcut uygulamalar irdelenmekte ve Antalya içmesuyu dağıtım şebekesinde türbin pompa kullanılarak fazla basınçtan enerji üretimi için pilot bir uygulama anlatılmaktadır.
Anahtar Kelimeler: İçme suyu iletim ve dağıtım sistemleri, yenilenebilir enerji, türbin, fazla su basıncının kırılması

1 Introduction

Availability and supply of water and energy sources play an important role for human life, economical and industrial development. Water demand increases due to urbanization and population increase and this causes an increase in operational costs of water distribution networks (WDNs). Global electricity consumption for pumping in water supply systems constitutes 2-3% of the whole consumption [1]. Water loss in water distribution networks is another important issue besides energy consumption. Country average water losses is estimated at 50% of the total system input volume in Turkey and water utilities are obliged to reduce it to economical levels. Management of water losses in WDNs rely on four basic methods: 1) Pressure management; 2) Active leakage control 3) Fast and high quality repair; 4) Pipe material selection and maintenance [2]. A well-known relation exists between water pressure and water losses in WDNs. As pressure increases, the amount of water leakage from pipes increases. Likewise, when pressure is reduced, the amount of water leakage is reduced. In 2014, a new regulation, *Water Losses Control in Water Supply and Distribution Systems*, has been promulgated and it has accelerated the applications to reduce water losses in WDNs. Up to recent time, maximum allowable static pressure in WDNs was set as 80 m water column in Turkey but it has been reduced to 60 m recently. Some measures are needed to control and reduce excess water pressure in water supply and distribution systems. Break Pressure Tanks (BPT), balancing reservoirs and Pressure Reducing Valves (PRV) are used commonly for this purpose. Excess water pressure in water supply and distribution systems increases risks for pipe bursts and causes high water losses. Contrarily, in case of very low water pressure, water cannot reach the consumers and it causes customer dissatisfaction. In gravity type water transmission lines, water is transferred from high elevations to low elevations. During this transmission, pressure in water pipes increases significantly and several BPTs, balancing reservoirs or PRVs are located to reduce excess pressure. In BPTs and balancing reservoirs, water is exposed to atmospheric pressure while being stored in the tank. In this application, excess water pressure and kinetic energy is dissipated and accordingly occurrence of excess water pressure is prevented. In gravity type water transmission lines, a turbine can be located before balancing reservoirs which can maintain energy recovery from excess pressure [3-5]. Occurrence of excess water pressure in a gravity type water transmission line and possible locations of turbines are demonstrated in Figure 1. Use of BPTs and balancing reservoirs in gravity type water transmission lines is very common worldwide and installation of turbines at the entrance of these units provides a big potential for energy production and contributes to sustainable water supply services. Power generation from a hydroelectric turbine can be calculated from Eqn 1. In this equation parameters are defined as follows: *P*, power (W);*Q*, flow rate passing through turbine (m³/s);*ρ*, density of water(≈ 1000 kg/m³);*g*, gravitational acceleration (9,81 m/s²), *H*, available head at turbine (m) and e_o, efficiency of whole energy generation system.

$$P = \mathrm{Q.\rho.g.H.}e_0 \qquad (1)$$

System efficiency includes the conversion losses from kinetic energy to mechanical energy and it is accepted as 65% in a safe estimation (including losses in turbine, energy conversion, energy distribution) [6]. As density of water and gravitational acceleration are known constants, flowrate of water and pressure are the main parameters for energy production from turbines. Installation of turbines at the entrance of BPTs and balancing reservoirs provides several advantages: energy production, reduction in carbon dioxide emissions and money income. Therefore, use of turbines in gravity type water transmission lines draws attention.

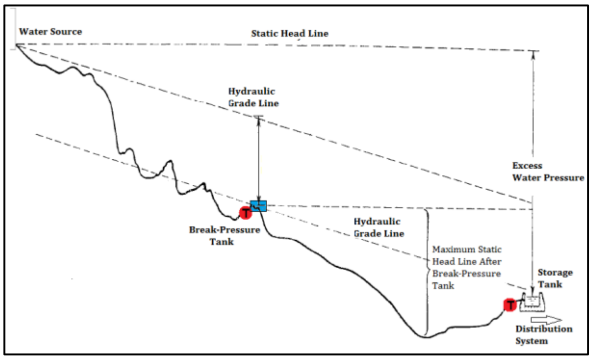


Figure 1.Illustrative scheme for a gravity type water transmission line where excess pressure occurs and possible locations of turbines to generate energy (T: turbine) [modified from 5]

In recent times, detection, reduction and management of water losses in WDNs gain more importance for sustainable water management. It is a common application to divide WDNs in small and isolated areas, called as District Metered Area (DMA) for better management of the network (See Figure 2). Total flowrate distributed within a DMA is measured at the entrance of the DMA using flowmeters. Continuous and regular data from flowrate measurement are used together with water meter readings of water subscribers to prepare water balance and to estimate water losses amount. Observation of Minimum Night Flow is possible at the DMAs and by evaluation of hourly water consumption and use of the prescribed methods, estimation of water losses is possible [7].

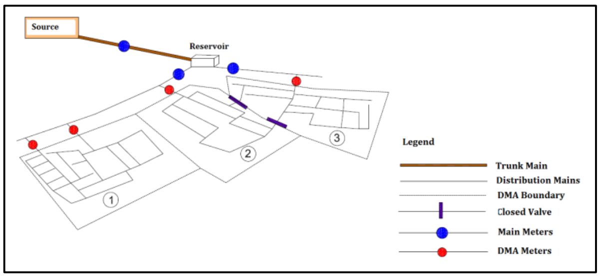


Figure 2.Illustration of a District Metered Area (DMA) [8]

In the current applications, population increase causes an increase in water demand and this causes an increase in energy consumption and energy costs for transmission of water. For sustainable management of WNDs, efficiency in water and energy consumption has to be improved. Water losses control is among the priority actions to improve energy efficiency in operation of WDNs. By reduction and prevention of water losses, energy conservation in the operation of WDNs can be accomplished. In addition to control of water losses, optimization of water transmission lines (arrangement of pumping schedules) according to the real water demands and use of SCADA (Supervisory Control and Data Acquisition) system gains importance. WDNs are rather complex systems and it is difficult to predict real time water demand and to manage these systems in terms of hydraulic and water quality targets. Therefore, mathematical models are commonly used to manage hydraulic and water quality issues. Many models have been developed to predict the variations in hydraulic and water quality parameters in WDNs till now. By use of these developed models, some improvements are achieved in operation of WDNs and realization of energy efficiency. Fossil fuels are used to provide energy for the operation of water supply and distribution systems and improvement of energy efficiency contributes to less carbon dioxide emissions. Use of renewable energy sources is the best approach to accomplish sustainability of energy use in water supply and distribution systems. There are three possible methods to provide energy for water supply and distribution systems. They are listed as follows: 1) solar, 2) wind and 3) hydroelectric energy. Table 1 presents various technological alternatives to provide energy efficiency. The high capital cost is the main obstacle for the mentioned alternatives.

Table 1.Technological alternatives for energy efficiency and conservation actions applicable to conventional water supply systems [modified from 9]

Energy efficiency and conservation technological alternatives	Energy efficiency and conservation action	Estimated energy savings
The use of renewable energy sources for pumping	The use of wind or solar pumping	Highly variable, according to the local potential
Hydropower recovery	The installation of hydraulic turbines and generators in existing water supply systems	Highly variable, according to the system layout and local potential
Pressure and water losses management	Pressure reduction (by using pressure reducing valves), pipe repair, active leakage control	The energy savings are proportional to the water savings.
Operational optimization	Real-time energy monitoring, operational optimization of pumping systems	5-20%
The use of efficient motor-pump sets	Correct pump sizing, selection of efficient pumps, replacing the belts by direct coupling, use of high efficiency motors	15-25% 2-10% 1% 5-10%
The use of variable speed motor-pump sets	The use of variable speed drives instead of valves	30-80%
The optimization of storage capacity and reservoir operation	The use of tanks for flow control and storage	10-20%
Optimized pipe and network designs	The elimination of bypass loops and other unnecessary flows, increasing the pipe diameters	5-20% 5-20%

Energy formed by available excess pressure and high heads in water supply and distribution systems can be recovered by using turbines or Pump as Turbines (PAT) instead of PRVs. The described applications are called as small scale hydroelectric production systems. In classification of small scale hydroelectric systems, the installation power is taken into account. The limits of small scale power systems vary from country to country (See Table 2). Micro-hydro systems are classified as power generating systems up to 100 kW. Selection of turbines or PATs is performed according to available head or excess pressure and flowrate [9]. Use of turbines in micro-hydro systems is not preferred due to their high costs and usually PATs are recommended for these systems. Accordingly, use of PATs for energy recovery from available excess pressure in WDNs remains as a viable alternative.

Table 2. Classification of hydro power systems [10]

Type	Station capacity	Unit capacity
Micro-hydro	upto100 kW	upto100 kW
Mini-hydro	101-2000 kW	101-1000 kW
Small hydro	2001-25000 kW	1001-5000 kW

In this study, mechanical equipment (hydro turbines and PATs) that can be used to generate energy from available excess energy in water supply and distribution systems are discussed by giving information about the possible alternatives and feasibility. Additionally, brief information about a pilot application within a research project conducted at Antalya City is given.

2 Material and Methods

In the first part of this section, hydro turbines and PATs are described as alternative mechanical equipment that can be used to generate energy from available excess pressure in water supply and WDNs. In the next part, information about mathematical models used for hydraulic design of WDNs is provided.

2.1 Pump as Turbines (PAT)

Hydroelectric energy production is a well-known technique and many applications exist worldwide especially in small scale. In order to provide the economical feasibility, the total system cost should be minimized. Use of PATs for energy recovery from excess pressure in WDNs is a promising technology. By using PATs, energy recovery from excess pressure is possible in addition to reduction in water losses. Pressure management is a common application to prevent water losses in WDNs. For better management and operation of WDNs, PRVs are commonly used to reduce excess pressure in WDNs down to optimum operational pressure levels. In order to determine the optimum operational pressure levels in WDNs, hydraulic models are used to simulate the network. Due to dynamic character of water demand in WDNs, use of hydraulic models presents a difficulty. A two-stage methodology is recommended to overcome this difficulty. In the first stage, location of PRV has to be determined. In the second stage, determination of time schedule for possible operation of PRV during a day is realized. Another method involves using conventional turbines to control pressure and generate energy. However, energy generation from excess pressure in WDNs is limited and a high cost is needed to make turbines smaller. The pay-back period is very long when costly turbines are used. Special design alternatives of turbines can be recommended but PAT systems have low initial cost and acceptable efficiencies which make them more advantageous [11].

PAT systems are centrifugal pumps which are similar to Francis turbines without flow rate control mechanism. Centrifugal pumps convert the pressure energy and kinetic energy into mechanical energy whereas Francis turbines convert pressure energy into mechanical energy. For this reason, if a pump is operated in a reverse mode, it works like a Francis turbine (See Figure 3).

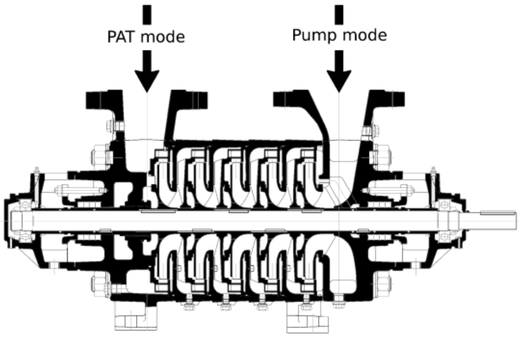
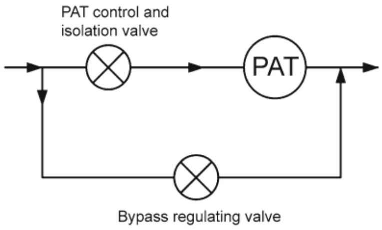
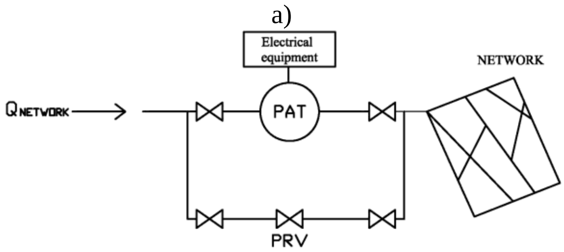


Figure 3. Cross sectional view of a two-stage centrifugal PAT [12]

In gravity type water transmission lines hydraulic properties (flow rate and pressure) are usually constant whereas they are both limited and subject to continuous changes in WDNs. The variations in hydraulic properties cause difficulties in design and operation of energy recovery systems. The high cost of the generator system required for energy production, highly varying hydraulic design parameters, relatively low efficiencies in micro scale hydroelectric power generation need to be evaluated carefully in feasibility studies. Practical use of PAT systems in WDNs is not common till now and the literature contains technical and economical analyses results. The installation cost for a miniaturized turbine costs approximately 1800 €/kW whereas installation cost of PAT system costs approximately 350 €/kW. The pay-back period of PAT systems are estimated to be less than 1 year. There are two alternatives for use of PAT system in WDNs as depicted in Figure 4. In the first alternative, PAT system is used alone whereas in the second alternative PAT and PRV systems are used in parallel [12-14].



a)



b)

Figure 4. PAT usage alternatives in WDNs, (a) PAT system alone [13], (b) parallel use of PAT and PRV systems [14]

2.2 Hydro Turbines

Hydro turbines can be classified in many categories based on usage area, power generation and power generation style. Hydraulic turbines are classified as impulse and reaction turbines. Pelton and Turgo turbines are the examples of impulse turbines while Francis and Kaplan turbines are reaction turbines (Table 3). Pelton turbine is one of the most effective impulse turbines (Figure 5). Pelton turbine extracts energy from the impulse of water. Computational Fluid Dynamics (CFD) uses numeric modeling tools to develop reaction turbines. However, modeling of impulse turbines is difficult because of head loss, secondary forces, surface tension, instability and internal reactions between components. Efficiency of Pelton turbines is affected by the structure of distributor, nozzle, bucket and casing [15]. Turgo turbines are reliable, robust and able to operate over a range of flow rates (Figure 6). Turgo turbines are usually operated at medium and high head. Turgo turbines extract energy from impulse of water as Pelton turbines do [16]. Although there are differences between Turgo and Pelton turbines, they are mostly classified in the same category. The most important difference between Turgo and Pelton turbines is that Turgo turbines can handle a higher water flow rate and be able to operate efficiently in lower head than Pelton turbines [17].

Figure 5. Thelayout of a typical modern Peltonturbine [15]

Figure 6.Turgo turbine [17]

Reaction turbines convert both kinetic and potential energy into mechanical energy. Francis turbines are used for heads up to 360 m while Kaplan turbines are used for heads up to 45 m. Kaplan turbines rotate faster than Francis turbines. Francis turbines are cost effective at medium heads while Kaplan turbines are cost effective at low heads. Typical layouts of Francis and Kaplan turbines are illustrated in Figure 7 and Figure 8. Efficiency curves of different turbines are illustrated in Figure 9.

Table 3. Turbine classifications based on different characteristics [18]

Based on head	Based on turbine shaft position	Based on direction of flow	Based on type of energy
-H>300 m High head - 400 m > H > 20 m Medium head -H<50 m Low head	- Horizontal - Vertical - Inclined	- Axial flow (Kaplan, Uskur) - Radial flow (Francis) - Diagonal flow (High speed Francis) - Tangential flow (Pelton, Banki) - Mixed flow	- Impulse turbine (Pelton, Turgo, Banki) - Reaction turbine (Francis, Kaplan, Uskur, Boru)

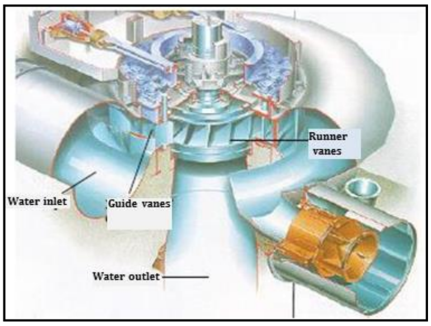


Figure 7.AxialFrancis turbine [18]

Figure 8. Kaplan turbine [19]

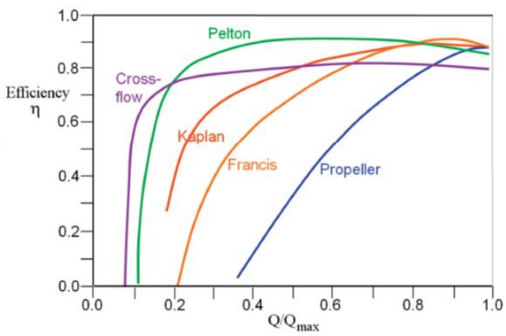


Figure 9. Efficiency curves of Kaplan, Pelton, Francis, Propeller and Cross-flow turbines [20]

2.3 Hydraulic Models

Levels and locations of excess water pressure in WDNs should be determined to recover energy from excess water pressure in WDNs. Hydraulic models can be performed to monitor changes in water pressure in WDNs. Level of water pressure in WDNs depends on pipe length, diameter, flow rate and velocity besides topography. Each WDN has different conditions; therefore hydraulic modeling is required to determine the levels of excess water pressure at each WDN. EPANET 2.0 is a well-known and widely used hydraulic modeling tool [21]. EPANET developed by US-EPA is free of charge. WaterGEMS is one of the most popular and user friendly hydraulic modeling software packages [22]. WaterGEMS*V8i* has almost all tools that might be needed for hydraulic and water quality modeling of WDNs. WaterGEMS is a comprehensive and easy to use water distribution modeling solution featuring interoperability across stand-alone, ArcGIS, AutoCAD, and MicroStation environments. All analysis performed using EPANET can be achieved by WaterGEMS whereas WaterGEMS*V8*i has additional scenario and optimization tools. Although data sets required for hydraulic and water quality modeling of WDNs is common in WaterGEMS and EPANET, WaterGEMS has predefined features such as Hazen-Williams roughness coefficient depending on type and age of pipe.

3 Results

A research project, funded by TUBITAK and titled as "Investigation of the Renewable Energy Recovery Potential for Sustainable Water Supply Systems" was initiated in November 2014 to investigate energy recovery potential from excess water pressure in WDNs and other environmental gains resulting from energy recovery. A pilot study area in Antalya City, namely Antalya ANFAS Expo Center, was chosen to apply this study (Figure 10 and 11). Changes in water pressure and flow rates, levels of excess water pressure in the study area will be estimated by performing EPANET and/or WaterGEMS software applications. A PAT system is going to be chosen and installed for the pilot study area considering changes in water pressure, flow rates and excess water pressure. Actual application in the study area will be accomplished after evaluation of estimated energy and changes in flow rates and water pressure levels.

Energy recovery application from excess water pressure will be carried out by installation of PAT in the study area where excess water pressure occurs. Performance of PAT system will be tested by monitoring energy recovery efficiency of system and water pressure and flow rates. Renewable energy generation and reduction in physical water losses will be derived by implementing PAT system in the pilot study area.

Renewable energy generation and reduction in carbon dioxide emissions will be calculated. Possible environmental gains are: renewable energy generation and reduction in carbon dioxide emissions resulting from renewable energy production; reduction in physical water losses, pipe burst frequency; use of less energy to extract, treat and supply water; use of less chemicals for treatment. The prescribed environmental gains will be investigated during the implementation of this project.

Figure 10. Antalya ANFAS-EXPO building and location of PAT application site

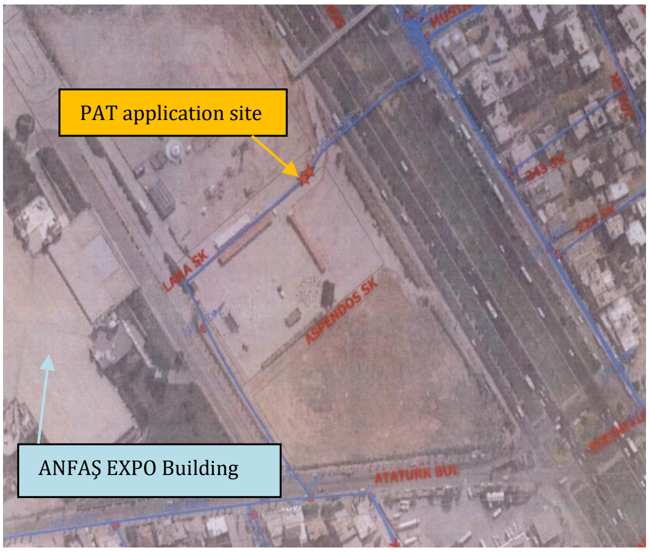


Figure 11.PAT application site and water distribution network of the pilot study area

Flow rates and water pressure levels at the entrance of pilot study area were obtained with an interval of 5min. from June 1-24, 2015 as depicted in Figure 12. Theoretical hydropower for each day was calculated considering 1 bar reduction in existing water pressure levels and calculated hydropower for each day of June 1-24, 2015 is depicted in Figure 13. For hydropower calculation, density of water, acceleration due to gravity, head and efficiency are assumed as 1000 kg/m^3, 9.81 m/s^2, 10 m., 0.7, respectively. Reducing water pressure in WDNs results in decreasing flow rates due to reduction in physical water losses. Within this study; changes in flow rates were ignored and flow rates obtained at the entrance of pilot study area were considered for calculations. Approximately 5 kW of hydropower generation is expected for June 2015.

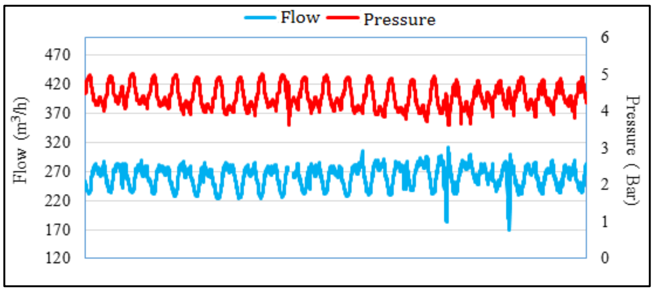


Figure 12. Flow rates and water pressure at the entrance of pilot study area (June 1-24, 2015)

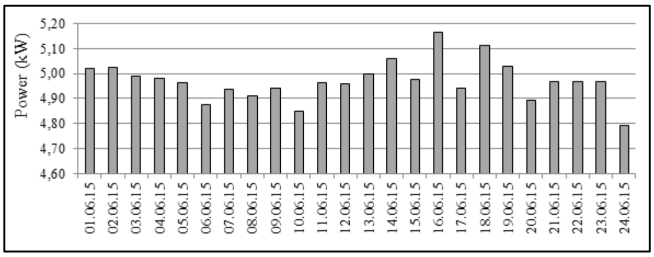


Figure 13. Theoretical hydropower generation for June1-24, 2015

4 Discussions and Conclusions

Renewable energy recovery plays an important role in implementation of sustainable water distribution networks. While PRVs and break pressure tanks are commonly used to reduce water pressure in gravity type water transmission lines, there are many applications in Europe and North America to recover energy from excess water pressure using turbines. Researches on energy recovery from excess water pressure in WDNs have been accelerated since energy efficiency became important. However, there are limited number of publications and on-site applications. There is not an actual application of energy recovery from excess water pressure in WDNs, although excess water pressure levels occur in WDNs. Both reduction in physical water losses and energy recovery can be achieved by replacing PRVs with PATs to reduce excess water pressure.

Energy recovery potential is going to be investigated and monitored by a real case application in Antalya. The results obtained from the ongoing research project "*Investigation of the Renewable Energy Recovery Potential for Sustainable Water Supply Systems*", funded by TUBITAK, will be evaluated. Performance of the first PAT application in Turkey will be evaluated for sustainable management of WDNs. Environmental benefits such as water losses reduction, energy recovery and water saving can be achieved by implementation of sustainable WDNs.

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