Investigation of Pumped Storage Hydro Electricity

Arsalan F. Latif, and Soorkeu A. Atrooshi

Abstract**—** In this work pumped storage hydro is studied within the context of numerical representation of the working equations with respect to two variables; head and flow rate. The results are verified against the outcome of a test rig, assembled for this purpose. Using the approved computational model, a parametric study has been performed to show the effect of the working parameters on such a system.

By increasing the flowing water temperature from (10-40 ^{o}C), the power production in the experimental rig indicated a reduction of (2.848 kW) when the friction factor in the penstock showed a reduction of (0.0025 e-3). The relation obtained between the head and the flow rate is linearly proportional and at specific working conditions it has shown (16.67%) reduction in flow rate over a height of (10m).

There are a large number of water storage and reservoirs available in this region of Iraq including over (60) sites in Erbil Province alone. Based on this study, it can be estimated that each source can help in generating (2-5 MW), which can collectively account for up to (15-40%) of the power demand in the region (Erbil; 36.1833^{o}N, 44.0167^{o}E).

Keywords**—** flow rate, head, hydro, pumped storage

I. INTRODUCTION

ONE of the greatest technical and commercial obstacles for renewable energy is energy storage. Weather a renewable energy source is available or strongest only at certain times of day, like solar and wind or available 24 hours a day like wave energy or run of the river hydro, making that electricity accessible when it is needed most is a challenge that must be overcome. The storage of electricity offers significant benefits for the generation, distribution and use of electric power. Combining some form of energy storage with a renewable energy source helps remove this uncertainty and increase the value of the electricity generated, [1].

Energy storage technologies can provide a vital link between the primary source of energy and its actual use. In particular, the inclusion of an energy storage system allows flexibility in matching the availability of an energy source to the demand profile in terms of where and when power is required and at what level, [2].

Despite the reduction in global rainfall levels and the increase in the frequency of draughts, pumping hydro is still one of the most established means of energy storage. It is rapidly deployable to the power grid as in a matter of minutes it can reach full capacity and in many cases a common network is used for hydro-power generation and pumping storage hydro. In the northern region of Iraq, there are more than (130) suggested potential sites for dam construction, figure (1), [3] which can actively participate in small-size pumped storage hydro systems.

It is aimed in this work to arrive at a verified computational model through comparison of head and flow rate with a minimal capacity experimental rig. The model is used to run a parametric study on the system performance and based on obtained outcomes; conclusions are drawn to the applicability of such a system in the region.

A. Environmental Issues, Hybrid Energy Applications and Economic Justifications

New state of the art hydro power plants have an efficiency of well above 93% and new pumped storage plants may have an energy ratio of 76% (European Commission, 2008), [4]. Based on the assessment and verification of the most efficient operation point with the best environmental implications, it is suggested that it is neither the electricity from thermal sources saved nor the cost saved at peak hours that should drive the decision on water pumping. The social profitability index should be the net increase in surplus, that is the difference between the larger gross surplus of an increased quality consumed at peak period but partially produced at low coast at off-peak periods on one hand, and the welfare loss of the off-peak period where more is produced than consumed on the other hand.

In villages and areas where it is difficult to be connected to a reliable source of electricity, pumped storage can play an active role in extending the power supply. The joint participation of solar, wind, with diesel generator back up [5], has already been discussed but the collective effect provided by including seasonal micro hydro systems supported by pumped storage is adding fresh environmentally justified momentum into off-grid power supply in mountainous areas.

In pumped-hydro systems pumps shutdown and changeover are major sources of instability and the complex dynamics and balancing of the process [6],[7],[8] are major causes of irregularities and deficiencies in the system. Therefore more emphasis is placed on improving the simulation of individual systems with different environmental and working conditions including the following setup indicated in this work, specific for improving micro-plant experimental verification.

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II. THEORY AND COMPUTATIONAL MODEL

The computational model divides the flow area into discretized elements. These elements are considered as separate control volumes in which the working equations rule. The working equations take into consideration the effect of property variation and friction factor for each element. The output of each control volume is considered as the input into the next section. Collectively they form the domain that is considered for investigation as the water flows through, from the upper reservoir into the lower reservoir.

The analysis of the dominating equations for hydropower generation is based on combining the basic mass, energy and momentum equations to establish the working equations for the flow, losses and the consumed time as derived explained and categorized in the following section bellow:

Water can generate power when it moves from a high potential energy state to a low potential energy state [9]. The change in potential energy (ΔPE) of water is:

$$\Delta PE_{water} = \Delta m_{water} \cdot g \cdot h \tag{1}$$

$$P_{out} = \eta_h \cdot P_{hydro} = \eta_h \cdot \rho_{water} \cdot g \cdot h_{eff} \cdot Q_{water} \tag{2}$$

For volumetric flow rate as in figure (2-a)

$$Q \cdot dt = A \cdot v \cdot dt \tag{3}$$

To calculate the volume consumed in (dt):

$$V = A \cdot dh$$

$$A_1 \cdot dh = v_2 \cdot A_2 \cdot dt \tag{4}$$

For a decreasing rate

$$dt = -\frac{A_1}{A_2 \cdot v_2} \cdot dh$$

Since for the same system, according to Torricelli: $v_2 \cong \sqrt{2 \cdot g \cdot h}$

$$dt = -\frac{A_1}{A_2} \cdot \frac{1}{\sqrt{2 \cdot g}} \cdot \frac{1}{h^{\frac{1}{2}}} \cdot dh \tag{5}$$

$$dt = -\frac{A_1}{A_2} \cdot \frac{1}{\sqrt{2 \cdot g}} \cdot h^{-\frac{1}{2}} \cdot dh \tag{6}$$

In the limit from (h_1) to (h_a)

$$\int_{t1}^{t2} dt = -\frac{A_1}{A_2} \cdot \frac{1}{\sqrt{2 \cdot g}} \cdot \int_{h1}^{ha} h^{-\frac{1}{2}} \cdot dh \tag{7}$$

$$(dt)_{t1}^{t2} = -\frac{A_1}{A_2} \cdot \frac{1}{\sqrt{2 \cdot g}} \cdot \left(\frac{h^{-\frac{1}{2}}}{\frac{1}{2}} \right)_{h1}^{ha} \tag{8}$$

$$\Delta t = -\frac{A_1}{A_2} \cdot \frac{2}{\sqrt{2 \cdot g}} \cdot \left(h_a^{\frac{1}{2}} - h_1^{\frac{1}{2}} \right) \tag{9}$$

$$\Delta t = \frac{A_1}{A_2} \cdot \frac{2}{\sqrt{2 \cdot g}} \cdot \left(h_1^{\frac{1}{2}} - h_a^{\frac{1}{2}} \right) \tag{10}$$

$$\Delta t = \frac{\sqrt{2}}{\sqrt{g}} \cdot \frac{A_1}{A_2} \cdot \left(h_1^{\frac{1}{2}} - h_a^{\frac{1}{2}} \right) \tag{11}$$

The total loss coefficient of the pipe is (kt) and it is equal to combining the minor (km) and the major (kf) loss coefficient as in figure (2-b):

$$v_2 = \frac{1}{\sqrt{kt}} \cdot \sqrt{2 \cdot g \cdot h} \tag{12}$$

Incorporating this into equation (11) gives:

$$\Delta t = \frac{\sqrt{2 \cdot kt}}{\sqrt{g}} \cdot \frac{A_1}{A_2} \cdot \left(h_1^{\frac{1}{2}} - h_a^{\frac{1}{2}} \right) \tag{13}$$

III. DESCRIPTION OF THE TEST RIG

The test rig was assembled to verify the findings of the computational model, developed in this work. The rig construction was carried out keeping in mind the simplest design to lower the costs and minimize the required time to make the experimental evaluation.

The test rig is composed of the following components as in figure (2, a & b). Two water tanks were used, the upper tank having the following dimensions; diameter = 0.564 m, tank height = 1.25m, and the dimensions of the lower tank were; diameter = 0.57 m, and tank height = 0.9m. They were made of galvanized steel, gage 0.4 mm, similar to the type used in residential units. Piping was made of PVC tubes with an inside diameter of 0.01905 m and the outside diameter was restricted to 0.025 m when the tube length reached 8m. One ball valve was used to control the descending flow of water from the upper tank and a pump (PK 60, 0.5 hp, 0.37 kW) was used to move the water from the ground level. The assembly of the components produced a small model of a pumped hydro-station. The two tanks represented the upper and lower reservoirs. The two reservoirs were connected by the PVC tubes, representing the piping network.

The turbine performance in the actual pumped hydro station was numerically modeled with the help of the figures from the exit flow line of the experimental rig passing through the pump (whose details were mentioned earlier) on the way down from the upper reservoir. Since this pump and its electrically driven motor are not designed to operate as a generator unit (tables 1 & 2 show rig data for 9.25 & 5m elevations), the obtained data were used with the micro turbines readings of similar flow rates from the literature, (table 3) to indicate the obtained output. Water coming down from the upper reservoir was stored in the lower reservoir to be pumped up again at the appropriate time.

IV. RESULTS AND DISCUSSION

In this work the obtained experimental results are presented for verification of the computational model and then the emphasis is placed on taking into consideration the working parameters that affect the performance of hydro-storage systems with a note for the feasibility of the pumping hydro-storage systems within the local framework, slightly underlining the available and established resources of hydro power in the region.

To distinguish between pump flow and pumped storage hydro it is important to identify the head as the available potential altitude in the storage reservoir and the flow rate as the corresponding flow out of the penstock into the turbine room. The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as $\mu_0 H$. Use the center dot to separate compound units, e.g., “$\mathrm{A{\cdot}m^2}$.”

A. *Verification of the computational model*

Figure (3) shows the depiction of computational against the experimental results for available head against the existing flow rate. The figure indicates the relation between the existing head and flow rate for both computational and experimental results at elevations of (5) and (9.25) meters. The results indicate (6.8465 %) deviation between the computed and experimental results for (5) and (4.433 %) for (9) meter head.

Figures (4) & (5) show the variation of head and flow rate with time, comparing the results obtained from the computational model with those acquired by the experimental rig. The curves indicate an inversely proportional relation with time for both cases of head and flow rate and at the same time, a comparison between the computational and experimental results. The maximum observed deviation between computed and experimental results for head was (6.8465 %) while for flow rate it was limited to ($2.08*10^{-4}$ %).

It is concluded from considering head and flow rate, which are the most important parameters in performance evaluation that the computational model performs satisfactorily and can be used for further parametric analysis.

B. The observed effect of temperature

Figure (6) shows the effect of temperature variation on the flow rate. The figure shows a slight proportional change in the flow rate with temperature change. For a temperature change of (40 - 10 ºC) which assumed to be approximating the seasonal water temperature change, a variation of 0.3 liters/min has been recorded. This is equal to (0.00038%) of the total flow rate which in this analysis was restricted to (78991.2) liters/minute.

Figure (7) shows the change in the turbine output according to the temperature change. The indication obtained from the figure is that in the temperature range (ΔT = 30 ºC) the power generation is changed by (0.002848 MW).
This is related to the variation in the flow and thermal characteristics of water and the way they are affected by the restricted temperature change and it generally indicates a reduction in output results in case of higher water temperature, for this temperature and flow range.

Figure (8) shows the effect of temperature change on the sum of the friction factors affecting the flow of water in the penstock to the turbine room. The figure shows a relation that is inversely proportional, for the specified temperature range of (30 ºC) a variation of (Δf = 0.0000025) has been recorded.

C. More realistic analysis based on comparative head and flow rates for actual pumped storage hydro

The acquired calculation skills were used to run a more realistic analysis based on much higher flow rates (500, 1000, 1500 & 2000 m^3/hr), to check the deviations induced by temperature variation, effective for pumped storage hydro. Figure (9) indicates the variation of flow rate for the recommended temperature change (10 – 40^oC). It is shown that the increase in temperature leads to a corresponding increase in flow rate and for the considered range of (10 – 40 ^oC) water temperature change, induces the increase of (0.361%, 0.56%, 0.726% and 0.874%) in flow rate, respectively. This outlines the fact that the stored energy is consumed faster in summer in comparison to winter. This conclusion is considerable for managing storage release and can be accounted for by reducing the flow area to achieve equal flows despite different water temperatures. Consequently, this improves the energy storage management and guarantees a more reliable energy storage system.

D. *The effect of head on flow rate*

Figure (10) shows the effect of head variation on the flow rate when other parameters are fixed. The relation is proportional and indicates that reduction in head leads to reduction in the flow rate. As shown in the figure; for the available range of almost (Δh = 10 m) the variation induced in the flow rate amounts to (16.667%) reduction in the flow. The reduction is because of the change in the kinetic energy of the flowing water inside the penstock, which is directly proportional to the potential head.

E. *Pumping hydro-storage electricity generation in the region*

The following discussion briefly outlines the potential for the application of pumping hydro-electricity storage in the different application contingencies for the region. It is attempted to base the argument on facts and realities of the region. The goal is to attempt to challenge the complex problem of satisfying the need and if possible exceeding the electricity demand even during the peak hours.

Figure (1) is constructed based on the available data from table (4), [3] to show the percentage of distribution of water resources in the region. It is obvious from the figure that Erbil governorate with its extended suburbia dominates the water resources category and there is plenty of potential for small dam construction. This in effect means that pumping hydro-electricity is a very attractive option to maintain these small reservoirs and promote their continuous power production.

Figure (11) shows the growth of demand and the state of power generation in the province of Erbil from 2005 to 2009, [10]. It is obvious from the graph that there is a soaring demand for electricity that is growing by the year. The figure also indicates that the power production has never been able to meet demand. The fact that the production of electricity shows some contradicting values when comparing the maximum produced amounts that should be able to meet the demand in the months of lower demand is related to the factors that affect the policies of power generation.

Water level issue is a very serious matter that can be properly boosted by the implementation of the pumping hydro storage. The fact that there are (133) potential sites for water storage, as indicated in figure (1), fully supports the idea and when appropriately implemented it can be an exceptionally clean supporting sources of peak and backup electrical power.

Figures (12 a & b) are based on the hourly readings for an average day in the two most extreme months of the year in electric power demand, [10]. According to the obtained data for the year 2009, the highest demand was recorded during an average day in the month of December while the lowest demand was observed during an average day in the month of October. Both graphs show that the period between 2 to 6 AM indicates the lowest demand. This period can be used to boost the storage or the potential for power generation. Pumping hydro-electricity storage can be used with the existing dams to redirect water from lower reservoirs to the main up stream storage area. The lower reservoir for the existing dams should be properly designed and be as environmentally friendly as possible. Also based on table (4) a sufficient number of water resources can be interconnected or individually employed for electric power generation that during the hours of lowest demand can be effectively reversed to work as a storage pumping station. The available four hour time (2-6 MW) indicated in figures (12 a & b) can provide the required time margin needed for both ideas discussed above.

V. CONCLUSIONS

1. The range and intensity of the parameters affecting the performance of a pumping hydro-electricity storage system can be identified and calculated by using the computational model developed in this work.
2. Increasing the temperature of water in the temperature range (10-40 ºC) leads to 0.95% increase in the flow rate.
3. Increasing the temperature of water in the temperature range (10-40 ºC) leads to (2.848 kW) reduction in output power production at fixed flow rate.
4. Increasing the water temperature leads to a reduction in friction factor in the penstock connecting the upper and lower units.
5. The relation between head and flow rate is linearly proportional and it depends on the actual altitude of water in the upper reservoir.
6. There is plenty of potential (around 60 sites in Erbil province alone) for the application of pumping hydro-electric storage systems. This indicates a level of storage that can play an effective role in supporting the power generation during the peak hours. Assuming (2-5MW) at support from each of these sites can lead to (120-300 MW) of supportive power. These amounts to (15-40%) of demand for the month of December of 2009.

NOMENCLATURE

Symbol	Definition	Unit
A	Cross Section Area	m^2
A_1	Tank Cross Section Area	m^2
A_2	Orifice Cross Section Area	m^2
g	Gravitational Acceleration	m/s^2
H, h	Elevation (Head)	m
h_{eff}	Effect Head	m
m	Mass of water	kg
P	Power Generation	W
PE	Potential Energy	J
Q	Flow rate of Water	m^3/s
t	Time	sec.
V	Volume	m^3
v	Absolute Velocity of water	m/s
v_2	Orifice Velocity of water	m/s

Greek letters	Definition	Unit
ρ	Density of water	kg/m^3
η	Hydraulic efficiency	____

Dimensionless factors	Definition
Kt	Total Loss Coefficient
Km	Minor Loss Coefficient
Kf	Major Loss Coefficient

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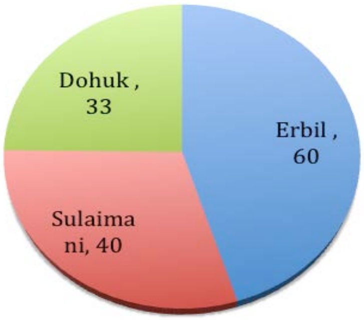


Fig. 1 suggested number of small dams to be constructed in the region.

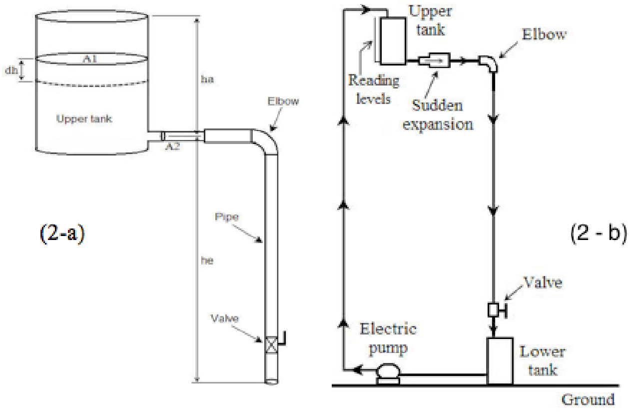


Fig.2 the layout of the experimental rig.

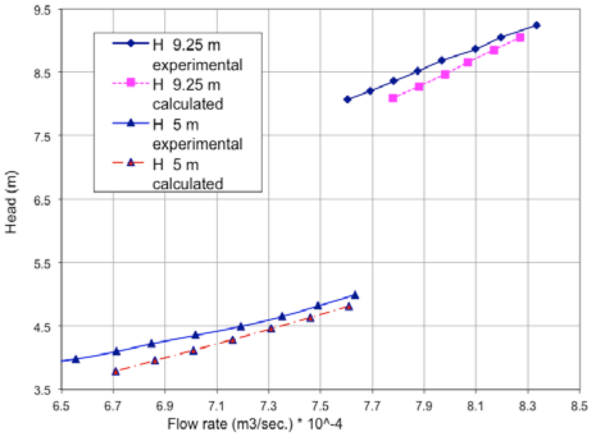


Fig. 3 variation of head with the available flow rate (5 to 9.25 m)

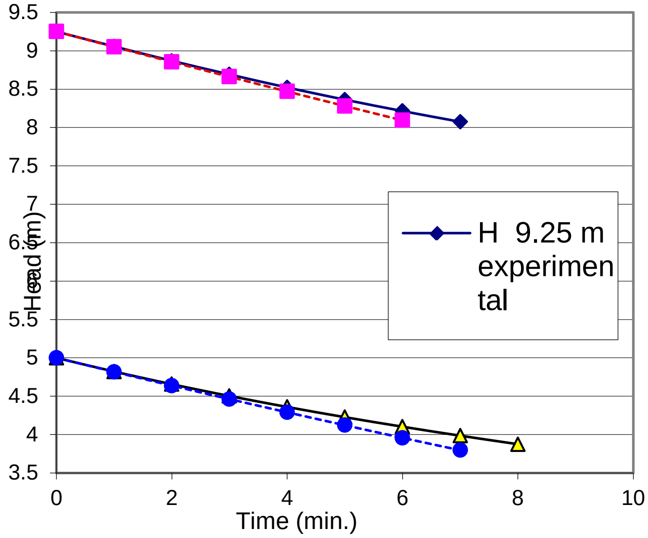


Fig. 4 depreciation of head with elapsed time (5 to 9.25 m)

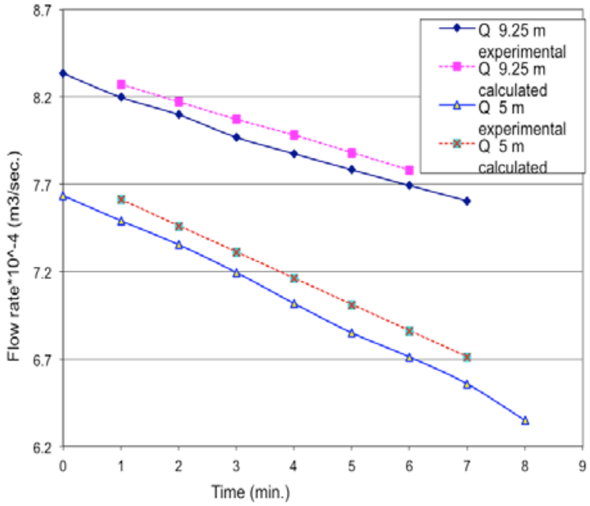


Fig. 5 depreciation of flow rate with elapsed time (5 to 9.25 m)

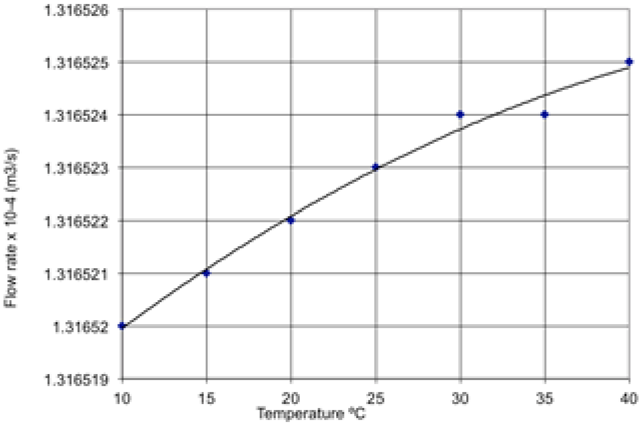


Fig. 6 variation of flow rate with to water temperature at constant head

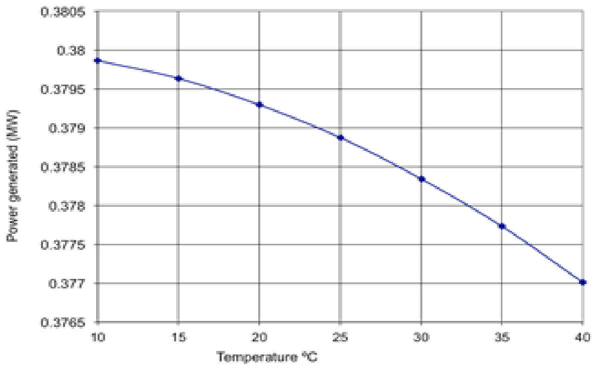


Fig. 7 variation of generated power with water temperature at constant head

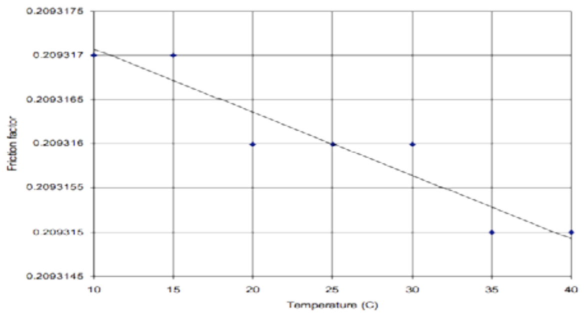


Fig. 8 variation of friction factor according to water temperature

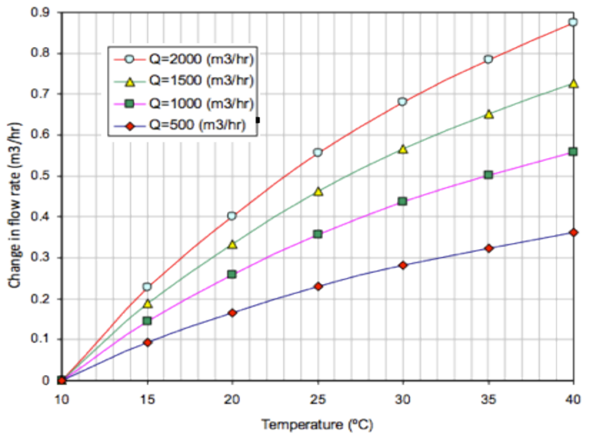


Fig. 9 variation of flow rate with temperature change at higher flow rates

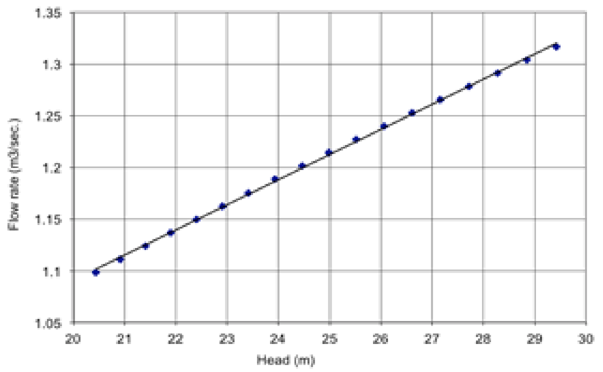


Fig. 10 relation between flow rate and head at constant temperature

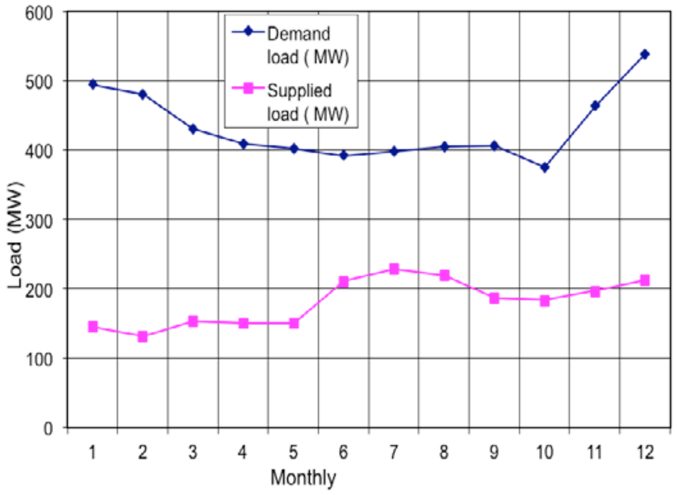
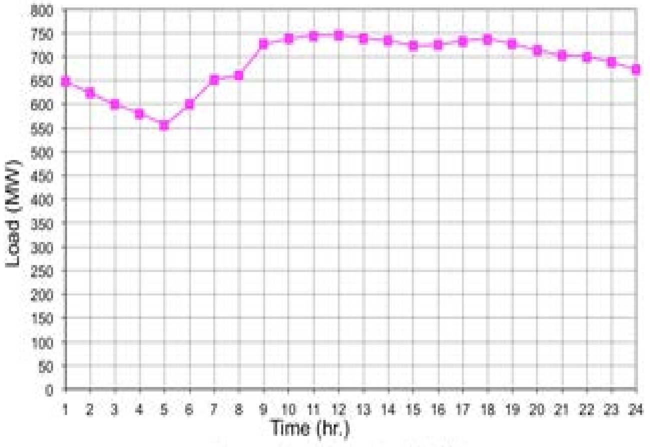
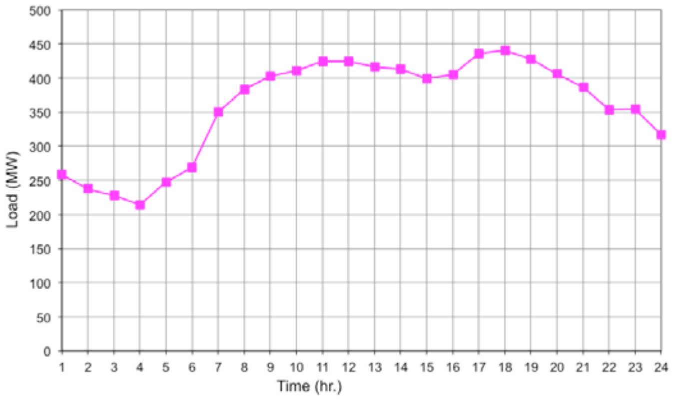


Fig. 11 average supply and demand load



Demand Load - December 20, 2009

Fig. 12a demand load for the city of Erbil for December 20th 2009



Demand Load October, 29 2009

Fig. 12b demand load for the city of Erbil for October 29th 2009