5ER-O31: Dynamic Modeling of Centrifugal Pump and its Performance Characteristics at Varied Speeds

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Abstract

In this paper a 270 MW centrifugal pump is modeled and results are compared with experimental data and Affinity results. The centrifugal pump provides 63.5 m3/hr flow rate and 380 m. static head at BEP (Best Efficiency Point). The dynamic model is able to capture any variation in flow rate results in corresponding variations of synchronous pump operational parameters. At constant speed mode, the synchronous centrifugal pump works at nominal speed immediately after start, regardless to the system characteristics. At varied speed, a controller adjusts the speed of the pump to the optimized speed regarding to matching the pump working point with the consumption point to save the energy. The performance characteristics at varied speed are recalculated. The model is simulated utilizing MATLAB /SIMULINK software with ode45 solver and variable step size.

Keywords: centrifugal pump, modeling, varied speed, pump performance characteristics

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Introduction

This research studied the performance of a pump hydro storage plant used variable speed synchronous machine in pumping and generating modes to cope with the proliferation of renewable generations. The research emphasized on the impact to the efficiency of a variable speed pump hydro storage plant at Lumtakong Chonlapa Wattana plant.

The purpose of this study is to obtain and evaluate the pump performance at different speeds. The result will give the opportunity for EGAT to storage and manage much effective operation at Lumtakong Chonlapa Wattana plant.

First, CFD model is used widely in Centrifugal Pump Numerical Simulation and Analysis in particularly, k-ε Turbulence model [1-4]. In order to obtain the pump performance, a series of steady numerical simulations of centrifugal pump at the design point and at eleven off-design points were carried out with the k-ε turbulence models.

According to the results obtained, the water head, shaft power and efficiency were calculated and the simulated performance curves of a centrifugal pump were compared with the experimental performance curves from EGAT test data. The result of the numerical simulation from the k-ε model had the best agreement with the experimental results.

It was confirmed that the model was suitable for the numerical simulation of the internal flow inside a centrifugal pump which we were going to vary its speed. By using CFD model, we obtained the head, power, efficiency and be able to evaluate the pump performance [5,6].

Second, a dynamics model of a centrifugal pump and piping system is modeled by Matlab/Simulink to study the varied speed operating conditions [7-8, 10-11]. The model consists of several main components: centrifugal pump, a fluid reservoir, pipeline, valve and necessary device. The simulation is conducted with a steady state operation In order to avoid some effects during the transient conditions such as fluctuation in flow rate, unsteady torque and angular velocity, the model is neglected the transient condition [9]. From this perspective, the model is able to give us some results reflect the real operation in the field. . The constant speed and varied speed method by affinity law are included in the model to study the varied speed operation [7-8].

Finally, this research evaluated the usage of a hybrid system between a variable speed pump in associated with a battery energy storage system to mitigate the fluctuation of a power flow. The obtained results can be used as a guide for planning of a grid scale energy storage system to handle with the increasing of renewable generations in the future.

Methodology

Pump Dynamic Model

The mathematical dynamic model is important in studying the pumping system. First, the pump dynamic model is studied and analyzed its fidelity. The pump dynamic model in this study consists of two parts, the mathematical dynamic model and Computational Fluid Dynamics (CFD) model. The first model is used to verify the pumping system. The second is used to study the variable speed pump in varied load condition. Also, the later model is used to compare the results computed by other methods which are proposed by the researchers in the literature.

- Equation of Pump Dynamics

Torque from the pump's shaft causes angular velocity. As a result, the inlet water flows from the inner radius to the outer radius. From Euler's equation, the equation describes the system as below.

$$H_p = c_1\omega^2 - c_2\omega Q \tag{1}$$

where H_{th} is theoretical head $(\Delta p / \rho g)$

ω ispump's angular velocity

$c_1,\ c_2$ is constant

When considering all losshappen in pump which is related to number of blades and figure of the blade, friction and loss due to flow configuration, equation(2) is rewritten as

$$H_p = h_{nn}\omega^2 - h_{nv}\omega Q - h_{vv}Q^2 \tag{2}$$

where $h_{nn},\ h_{nv},\ h_{vv}$ are found from experiments

Angular momentum can be calculate from equation(3)

$$M_p = \rho g\left(h_{nn}\omega Q - h_{nv}Q^2 - h_{vv}\frac{Q^3}{\omega}\right) \tag{3}$$

From Newton's second law,

$$J_p\frac{d\omega}{dt} = M_{motor} - M_p - M_f \tag{4}$$

where J_p is Moment of inertia of motor and pump

M_f isfriction torque from equation (5)

$$M_f = M_{f0}\,sin(\omega) + M_{f1}\omega \tag{5}$$

where M_{f0} isCoulomb friction

$M_{f1}\omega$ isviscous friction

From the momentum balance, the head of water of the pump system $\left(H_{sys}\right)$

$$H_{sys} = a_F \frac{dQ}{dt} + h_{rr}Q^2 + H_{static} \tag{6}$$

where h_{rr} is friction coefficient of the pipe

a_F is pipe's constant $\left(l / gA\right)$

H_{static} is upper water level

- Computational Fluid Dynamics Model of Pump

In this section, we describe the computational fluid dynamics model of the centrifugal pump. We model the pump by using **Ansys** program with *k*-ε turbulence flow assumption.

Firstly, the impeller and volute of the centrifugal pump are modeled. The conditions and details are listed below.

Pump Solid Model

The detailed specifications are in table 1.

Table 1 Specification of the blade in design

Design	Specification
Flow rate (Q)	63.5 m^3/s
Head (H)	380 m
Rotating Speed (N)	429 rpm
Blade number (Z)	9
Inlet Diameter (D1)	2392.2 mm
Outlet Diameter (D2)	3967.6 mm
Inlet Angle (β1)	15.91degree
Outlet Angle (β2)	22.79 degree
Blade Thickness (S2)	119.0 mm
Hub Diameter (b2)	939.9 mm

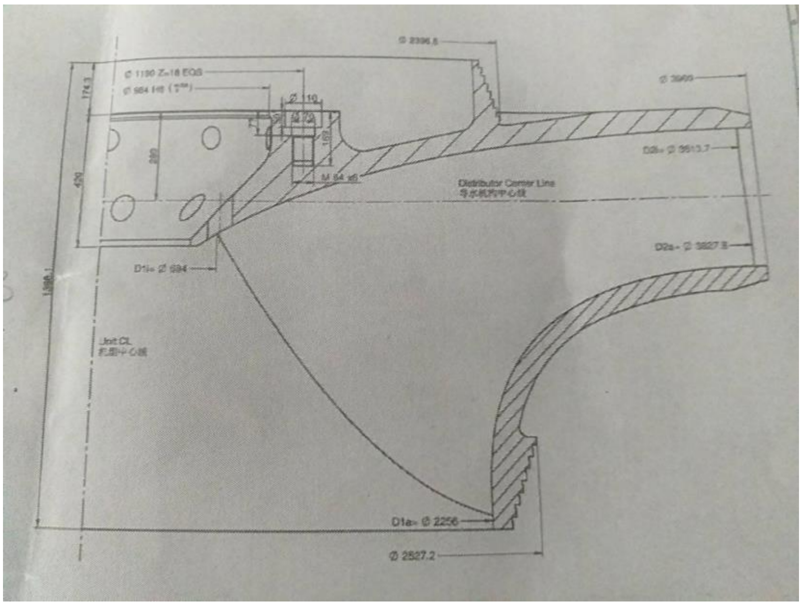

Figure 1. Cross section view of the blade

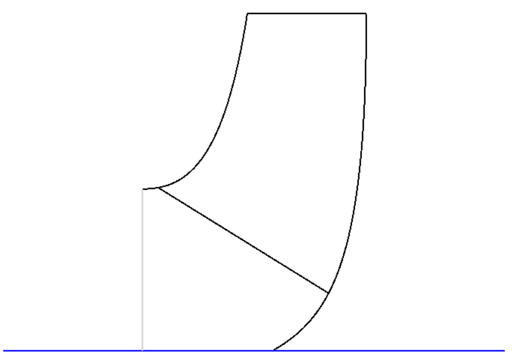

Figure 2.Meridional Blade

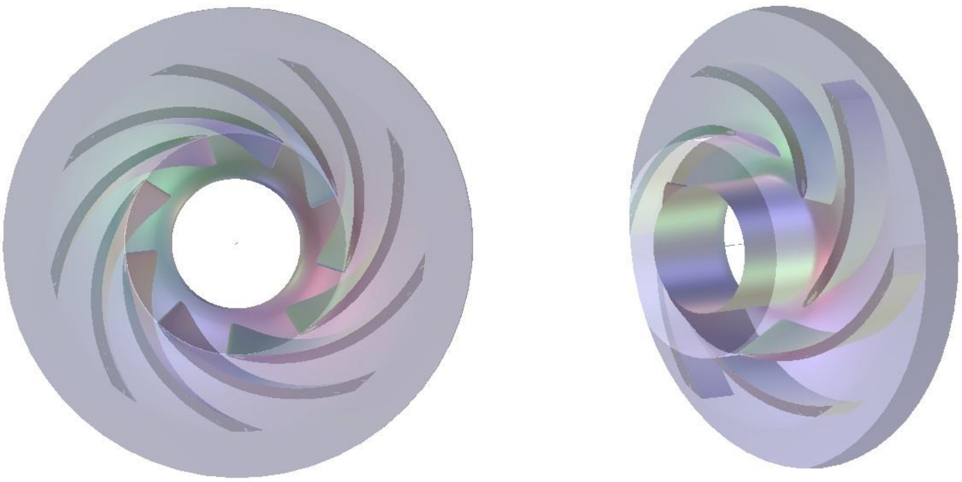

Figure 3.Impeller in 3D model

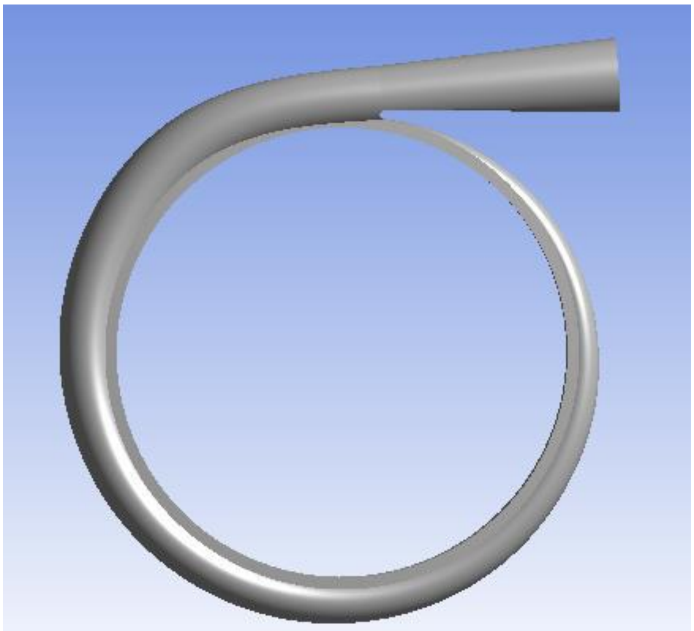

Figure 4. Volute

Calculating Condition

- Navier-stoke equation considering the mass conservative equation, momentum conservation and energy conservation.
- Sliding Mesh theory
- $k-\varepsilon$ and $k-\omega$ turbulence model for unsteady flow of incompressible fluid
- Tetrahedral Mesh modeling with 90343nodes and 272411elements
- Convergence iswhen the inlet water flow rate at impeller equals to the outlet water flow rate at volute. Assuming frozen rotor, this causes the water in the impeller relatively stalls with the wall and surface of the impeller.Thus, the water has the same amount of the velocity and the direction as the impeller
- Relative tolerance isless than $1\text{x}10^{-5}$
- Boundary condition are listed in Table 2
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Table 2 Boundary Condition

Analysis Type	Steady State
Mass flow rate	kg/s
Fluid	Water
Turbulence Model	k-ε
Residual Type	RMS
Residual Target	IE-6
Interference	Rotor Frozen
Static Pressure	0 atm
Reference Pressure	1 atm

Simulation Results

From figure5, the rotation of the impeller raises the water pressurealong the radius. The water enters the pump at the center of the pump. Next, the impeller will cast the water along the angle of the impeller. This increases the momentum and pressure of the water. From Euler theory, one can obtain the pressure from calculating the change in momentum of the water.

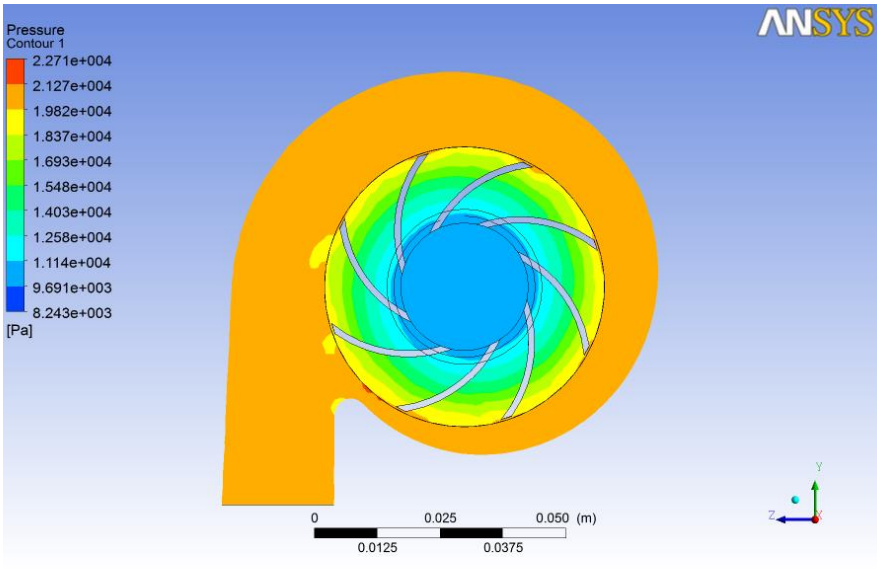

Figure 5 Pressure distribution

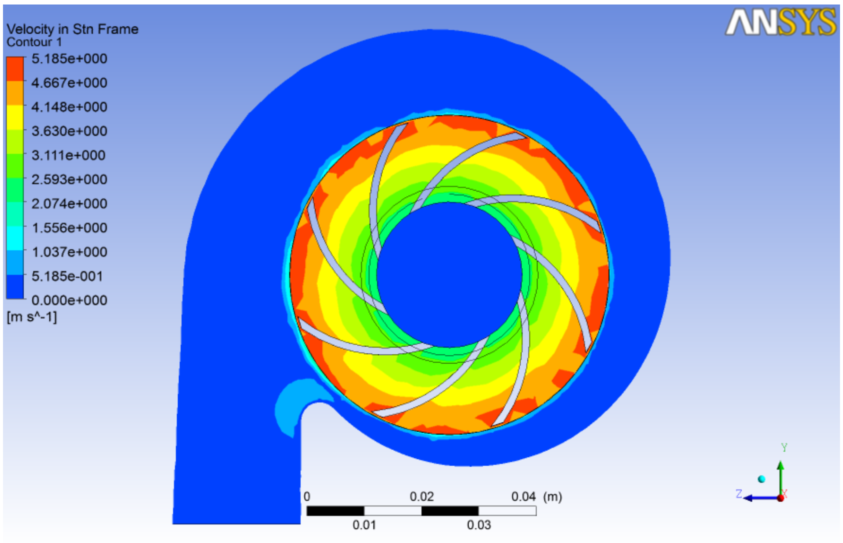

Figure 6 Velocity distribution

From figure 6, wecan observe the velocity distribution inside the pump where the water increases the velocity from the inlet at 0.3 m/s. Next, the water continues increasing the velocity along the impeller and reaches the maximum velocity at the exit at 5.85 m/s. Later, the water reduces the velocity due to collapsing to the volute's wall. From Navier-stoke equation, the kinetic energy is changed to the potential energy in the form of the static pressure.In Figure 7, the shear stress and vortex is shownin vector form.

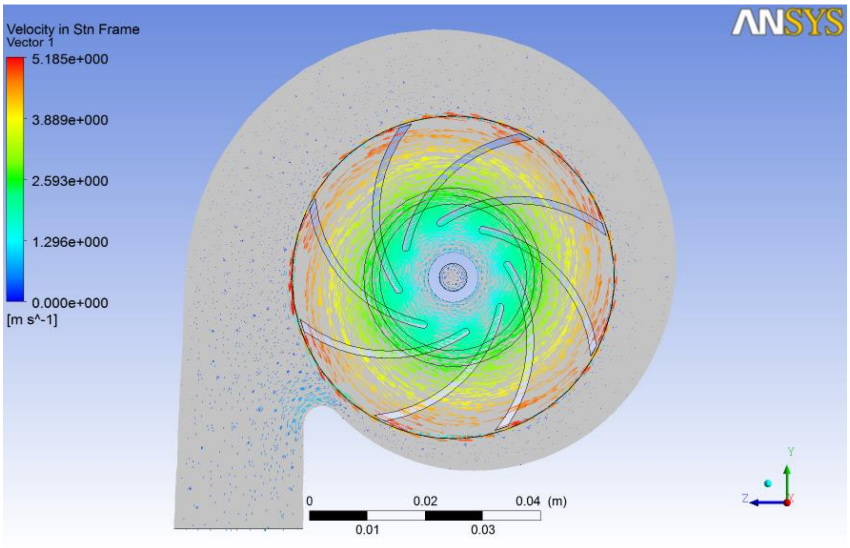

Figure 7 Vector of flow velocity in Pump

Pump Performance

The pump performance from the computational fluid dynamics model is illustrated in Figure 8

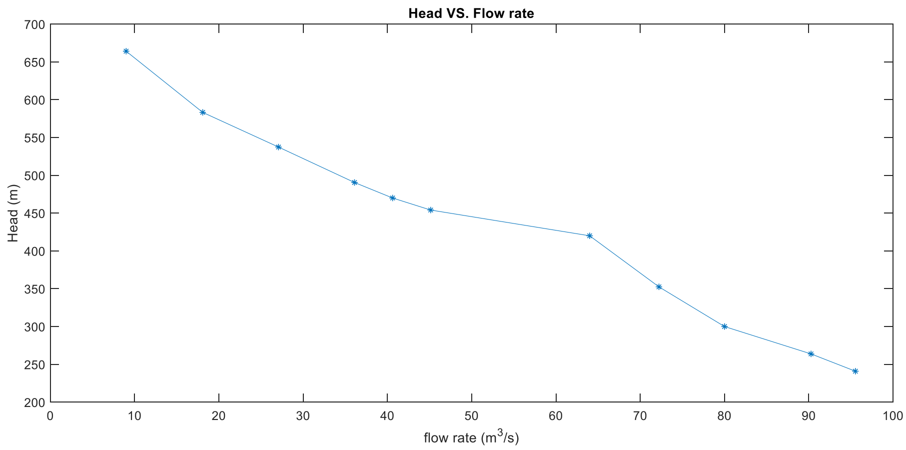

Figure 8 Water Flow Rate (m^3/s) VS. Head (m) at speed 429 rpm (100%)

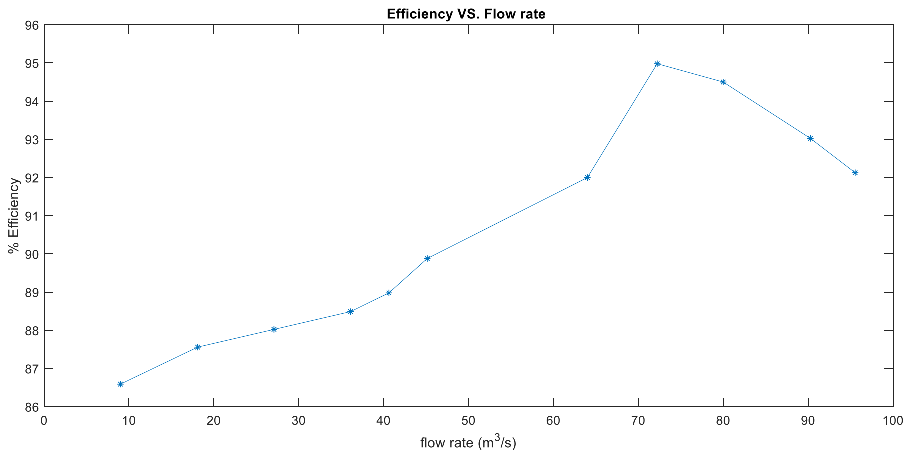

Figure 9 Pump Efficiency VS. Flow Rateat speed429 rpm (100%)

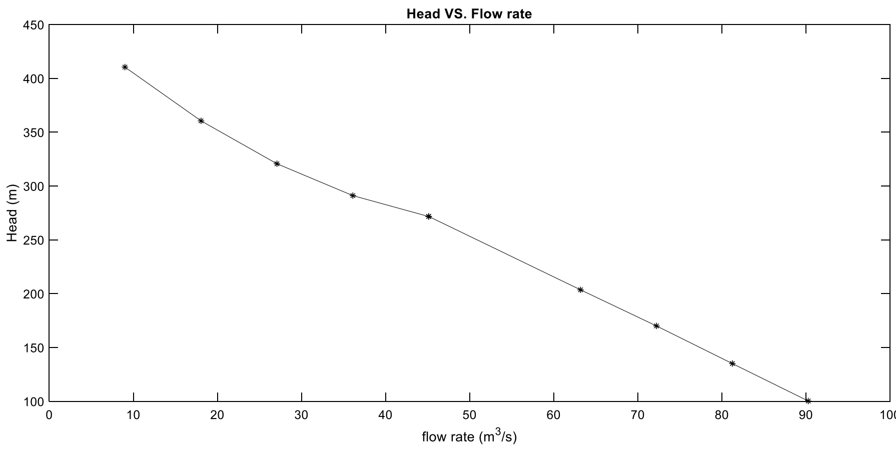

Figure 10 Water Flow Rate (m^3/s) VS. Head (m) at speed 343rpm (80%)

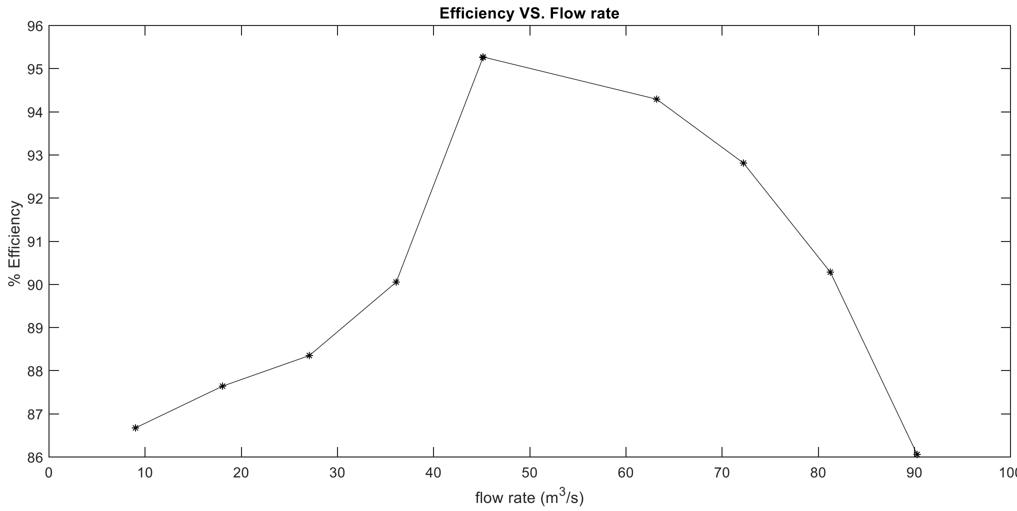

Figure 11 Pump Efficiency VS. Flow Rateat speed 343rpm (80%)

From Figure8and10, we find that when the water flow rate increases, the head will decrease. From Figure9and11, the pump efficiency increases when the water flow rate increase. When it reaches the maximum point the graph recedes. Figure 12 show the comparison of the efficiency at 343 rpm and 429 rpm.

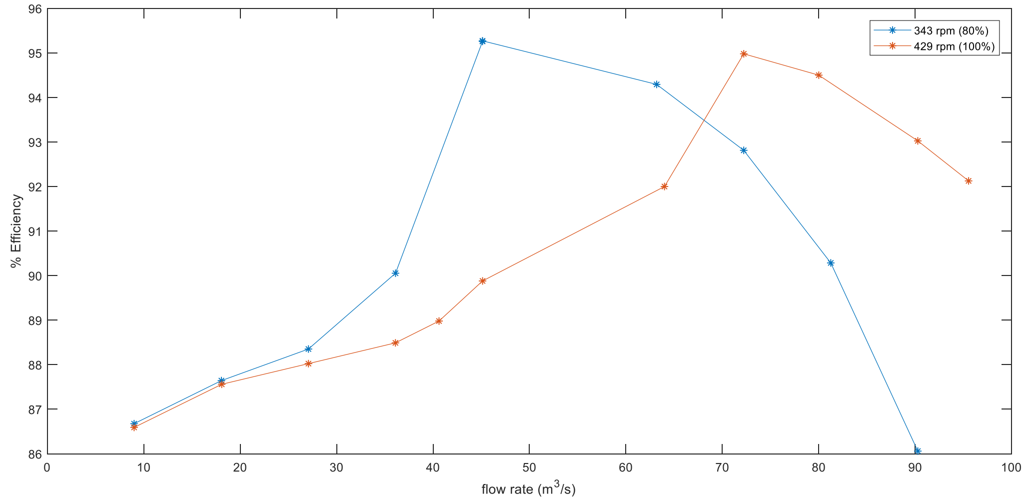

Figure 12 Comparison of the Efficiency at 343 rpm and 429 rpm.

From Figure 12, the efficiency curve moves to the left after reducing the pump speed. Similarly, in Figure 9 and 11, at100% (429 rpm) and 80% (343 rpm) at the same operating point, the pump efficiency reduces when the speed is decreased.Thus, by decreasing the pump speed, the operating point moves to the left. As a result, the efficiency is increased. Controversy, the pump head decreases as shown in Figure 13. The study in this section will be used to interpret the results in next sections.

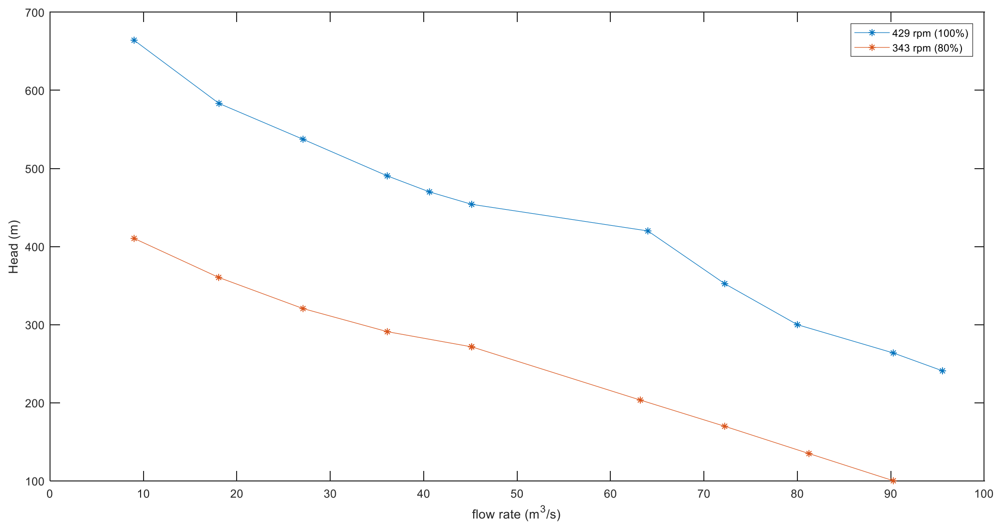

Figure 13 Pump Head at 429 rpm (100%) and 343 rpm (80%)

Pump System at LumtakongChonlapaWattana plant.

In this section we use the results from the previous section to analyze the operating of the pump system at LumtakongChonlapaWattana plant.

The preliminary assumptionconsidering

- upper pond is assumed to be an open system with constant area

- Simplified mathematical equations are used to model the pumping system, pump, components and fitting. The calculation is compared to the data from EGAT at LumtakongChonlapaWattana plant.
- Static pressure which is measured from lower pond and upper pondused to find the friction factor in the system
- Affinity law for recalculate pump head and flow ratefor newpump performance curve

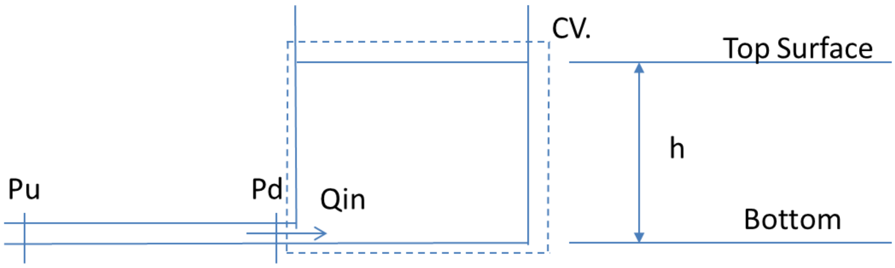

Figure 14 Simplified the pumping system at LumtakongChonlapaWattana plant.

From Figure 14,control volume is the upper pond. Pump gives raised pressure to the water, $P_u$which adequate to compensate the loss in the pipe system and elevation. There isflow rateQ_{in}. From the continuity equation yields

$$\dot{V} = Q_{in} + \frac{V}{\beta}\dot{P}_{CV} \tag{7}$$

Assuming the water is incompressible fluid.Volume of the Upper pond is 10.3x10^6 m^{3}which is less thanwater's bulk modulus (2.34x10^9 P_a). Thus, the second term can be neglected.Equation(7) is rewritten as

$$\dot{V} = Q_{in} \tag{8}$$

The change of the upper pond volume

$$\dot{V} = A\dot{h} \tag{9}$$

For inertia dominated flow,

$$P_u - P_d = RQ_{in}^{\ 2} + H_S \tag{10}$$

Assuming downstream pressureis the pressure prior to enter the upper pond.The rate of change of the surface of the upper pond is calculate fromequation (11)

$$\dot{h} = \frac{1}{A}\sqrt{|P_u - \rho gh|}sign(P_u - \rho gh) \tag{11}$$

MATLAB/simulink model of the whole system is shown in Figure 15.

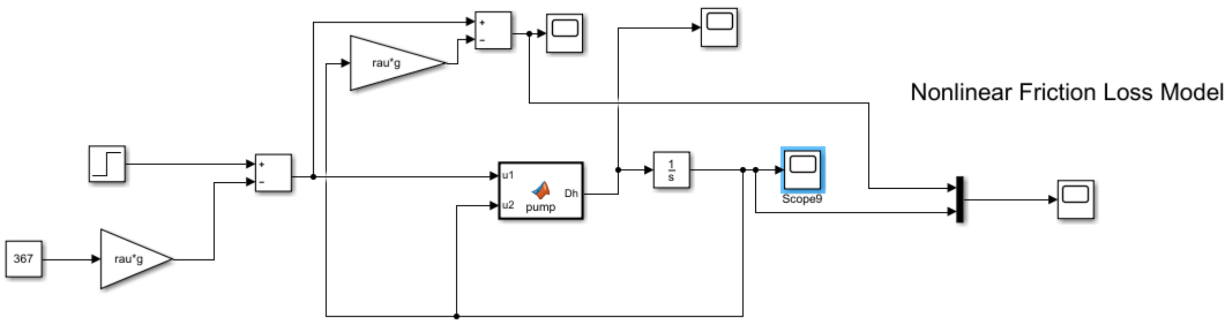

Figure 15 MATLAB/Simulink Model of Pumping System

Table 3 Comparison between Calculation and Recorded data

condition	TDH(m)	water level(m)	Flow (m^3/s)	Energy MWh	Energy out (MWh)	efficiency
recorded date (full speed)	378	640	63.38	243541.999	235047.704	96.512
simulation (95% speed)	384.4	640	61.6	243541.999	236094	96.9
simulation (92%speed)	383.6	640	0	0	0	0

From the simulation at the varied pump speed at 95% and 92%, the results are shown in Table 2 where the full speed has 378 mhead, flow rate at 63 m^3/s and efficiency 96 %.

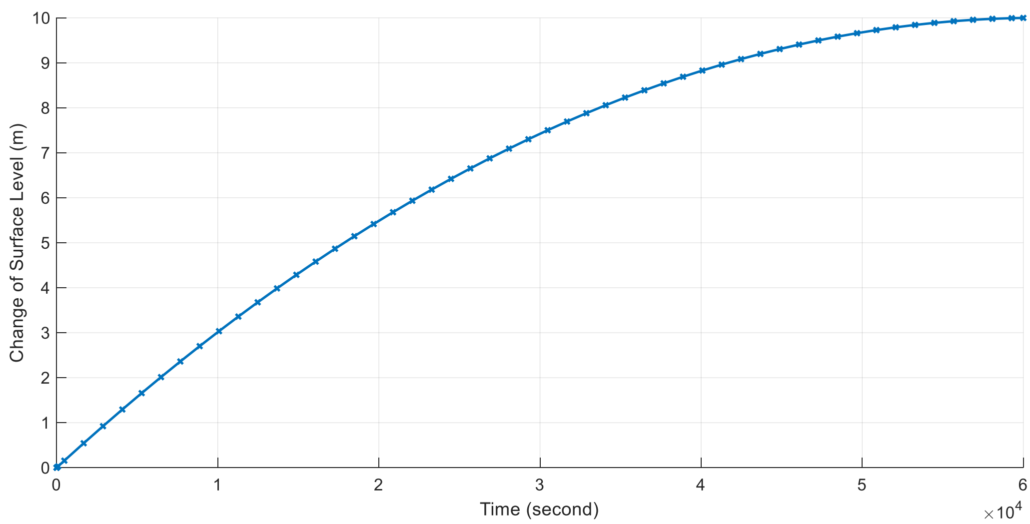

Figure 16 Water Surface at the Upper pond on YaiTieng Mountain at 95% (407.1 rpm)

From the simulation,Figure16 atspeed 95% (407.1 rpm), pump can raise the water to the upper pond in 16 hour at 384.4m head andflow rate at 61 m^3/s. When the speed is reduced to 92 %, the pump head is at 383.6 m. Figure 17 shows the simulation of the water surface at the upper pond at 92% speed. Although, the curve shows that the pump successfully deliveries the water up to the upper pond, consumed time is very long. Thus, it is impossible to operate. From Affinity law, we find out that this pump cannot achieve the requirement at reduced speed. This will be discussed in next section.

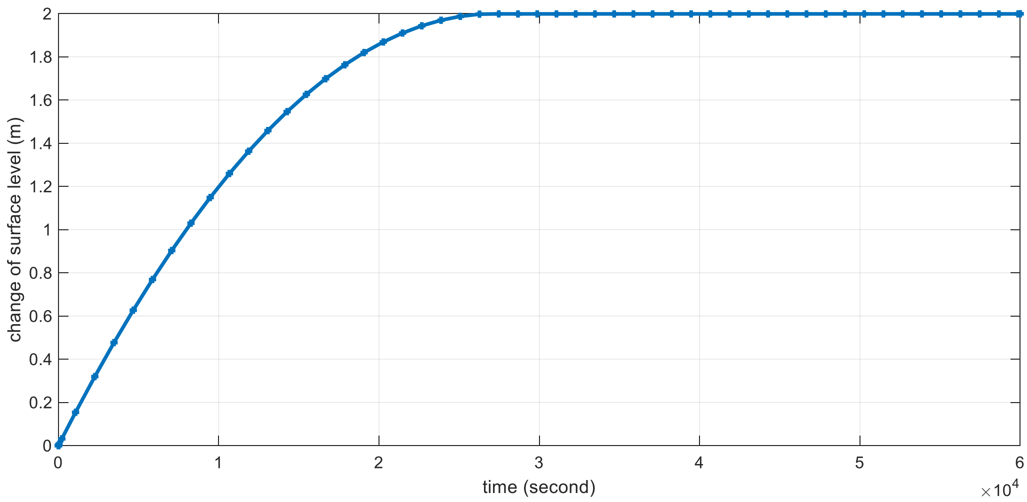

Figure 17 Water Surface at the Upper pond on YaiTieng Mountain at 92% (394 rpm)

FromAffinity Law, the pump speed is varied from100 %at 428.6rpm to 95%,90%, 80%, 70%, 60%and50% . The head pump and the flow rate can be recalculated as illustrated in Figure 18.

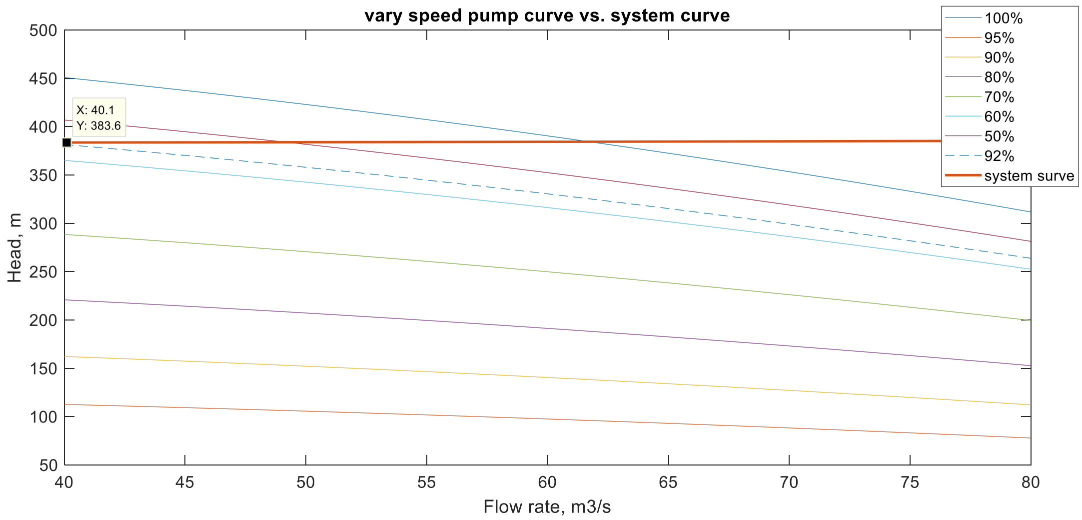

Figure 18 Pump curveat varied speed byAffinity Law

Figure 18, the operation point is the intersection between the pump curve and the system curve. The recorded data from EGAT, at the operating point the pump operates at 100% full speed and had head of 384.4 m with the flow rate at 61.7 m^3/s. After varying the pump speed to 95% and 92%, the head is 383.9

m and 383.m, respectively. However, the flow rate at 92% speed is at 40 m^3/s. At very low flow rate, the pumping system cannot be really operated in practical, since it takes too long to pump all the water as required.

Conclusion

The study shows the benefit of the pumping system at variable speed mode. The pumping system design usually selects the pump that fits to the design criteria first. There are few gaps to adjust and modify for the best efficiency. To vary the pump speed, the designer has to design at the beginning, especially for the mechanical part. The pump dynamic model is studied and analyzed. The CFD pump is very useful when there is need to reconstruct the pump performance curve. The simulation results can be used to analyzed the pumping system at LumtakongChonlapaWattana plant.

Acknowledgement

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