Reliability of parallel and serial centrifugal pumps for dewatering in mining process

***Mohammad Emal Qazizada*[1]** *and* ***Elena Pivarčiová*[1]**

In the mining process, besides the semiliquid mixture, mud, slurry, and rocks, there are large volumes of water to remove in order to keep production moving. The present paper will determine the application of centrifugal pumps connection in series and parallel form for dewatering in mining industry process. Initially studied the reliability of a centrifugal pumps connection in parallel and serial at a different frequency of rotation (DFR) and flow rates, to measure the behaviour of the head and flow of fluid transported. The process of calculation completed for a different rotational set of frequency for parallel and series connection, the head, hydraulic power, mechanical power, pump efficiency, and net position suction head required calculated in (2200, 2600. 2800 and 3000 [r.p.m]) respectively. The determination of energy efficiency and reliability based limits for the recommendable operating region of a variable speed driven (VSD) are discussed. As well focused to analyse the performance of individual characteristic curves of the serial and parallel centrifugal pumps. The application part considers the suitable operating conditions for VSD controlled pumping system and the basic options for monitoring the flow rate of each parallel and serial pumps. In addition for dewatering mining industry process to transport higher flow rates parallel pumps connection, and for higher discharge heads serial pumps connection are discussed, the head capacity can be increased by connecting more pumps in series, or the flow rate capacity can be increased by connecting more pumps in parallel. As well specific energy consumption of the serial with parallel pumping system could be optimised with individual pump. More results of realising (DFR) and (VSD) in real life of series and parallel systems could be gathered with simulated and experimental system situations. The advantage of pumps connection in parallel and serial configuration guarantee quality, reliability and transport maximum performance at minimum cost.

Keywords: *Pumps connection, VSD operation, reliability, Mine dewatering, Height head, huge volume*

Introduction

Centrifugal pumps are used in various industries and considered as one of the most important components in any processing equipment that should be preserved with fluids as an important part of its business. Centrifugal pumps are usually part of a larger system, and therefore their reliability can affect the productivity of system. In the viewpoint of reliability, considerable attention has been paid to centrifugal pumps in recent years (Erickson et al., 2000). Centrifugal pumps are one of the most important mechanisms in any liquid transport process. Reliability and maintainability of a centrifugal pumps in overall access play an important role in proper maintenance strategy (Singh et al., 2013).

More results of realising energy savings in real life pumping systems could be gathered with simulated and experimental system situations. Especially case examples for pumping systems serial and parallel would give interesting information of the benefits of the proposed strategy. The dewatering operation in the mining process is significantly important because the mine water is intensely treating the environment by natural resources, environmental degradation and pollution of the environmental (Stojiljkovic et al., 2014). At present, industrial water and acid mine drainage (AMD) are considered as the main sources of water pollution in many countries (Švandová et al., 2016). Various technologies have been proposed to deal with dewatering of mining processes, such as absorption, filtration, membrane technology and physical, mechanical, biological, and photochemical method (Sviatskii et al., 2016). The connection of centrifugal pumps in series and parallel system assists in removing the ground water, which is a common problem in the mining process, and developing a mine below groundwater level presents many challenges. Poorly controlled groundwater will have negative impacts on the safety, efficiency, and economics of mining operations. If groundwater can be controlled by a planned program of dewatering (GWE, 2013).

This article concentrates on the methods that allow the analysis of parallel and serial centrifugal pumps reliability performance operation of a frequency converter computer controlled, as monitoring of analysis device. Computer controlled frequency converter required in automated and in practice by current demands, computer-aided technology must often are used (Božek, 2013). First of all, the determination of energy efficiency, reliability based limits for recommendable operating region of variable speed driven VSD, and then calculating the head, hydraulic power, mechanical power, net position suction head are reflected for laboratory pumping system (Qazizada et al., 2016).

The paper focused on series and parallel connection centrifugal pumps system that are commonly used in the mining industry, municipal pumping applications, and the laboratory tests have been carried out. However,

[1] *Emal Qazizada Mohammad, Elena Pivarčiová*, Technical University in Zvolen, Faculty of Environmental and Manufacturing Technology, Department of Machinery Control and Automation Technology, Masarykova 24, 960 53 Zvolen, Slovakia, qazizada198@gmail.com, pivarciova@tuzvo.sk

the methods studied according to the objectives of this paper can also be applied to other centrifugal pump types, such as axial flow pump, gear pump and peripheral flow pumps, if allowed by their characteristics. The methods observed the using of centrifugal pumps reliability analysis based on the characteristics of functional curves and reliability at various speeds of rotation.

This paper focuses on three actions of parallel and serial centrifugal pumps connection systems: the first part of action considers practical conditions for VSD-controlled. The second part of action focuses on basic options for monitoring of flow rate for each parallel and serial pumping system. The third part describes the application of methods for applying energy efficiency control strategy in a VSD controlled system. In our paper, we focused on the visualisation of pumps specifications in the proximity to obtain suitable results from research (Brodnianska, 2016).

Many authors were completed their research in the area of dewatering in the mining industry process and reliability analysis of double connection centrifugal pumps system. Kimberly, Pyzdrowski, Schiller and Smith start to understand the basic of centrifugal pump operation, by starting from such fundamentals as head and pressure, the authors have developed practical tips for specification and operation that provide for cost-effectiveness and reliability (Kimberly et al., 2002). Sivakumara. Ramezanianpourb and O'Halloran worked with Mine Water Treatment Using a Vacuum Membrane Distillation System (Sivakumara et al., 2013). Flygt and Godwin are brands of Xylem, and this group wrote the dewatering pump handbook for mining process (Xylem, 2013). Tru-Flo Pumping Systems provides the Heli-Flo dewatering pumps system for mining industry process (Truflo, 2017). Viholainen, Kortelainen, Ahonen, Aranto and Vakkilainen, studded methods for the control of serial and parallel–connected pump systems by a computer control frequency converter have been proposed in (Viholainen et al., 2009). Božek worked on research that it is necessary to be concerned about automation data gathering about device component (Impeller, Shaft, carcase, bearing) operation mode in real conditions (Božek, 2014).

Material and methods

The methodology of mine dewatering and demonstration of parallel and series pumps connection

The mine dewatering process at the extraction well can be divided into two parts. First part is the well pump, which brings the mine water from about 120 m deep to the surface and delivers it with a pressure head of 3 bars to the pressure boosting system. The second part is the pressurised boosting system which provides the distribution and required pre-set pressure at the connected clusters and buildings. Because the system needs to operate fully automatic and demand-driven a pressurised buffer system for a start or stop operation of the well pumps is applied in the case that the distributions flow is less than the required minimum flow of the well pumps (Verhoeven, 2014). Parallel centrifugal pumps applied in parallel when they receive liquid from the same suction manifold, and discharge into a common discharge manifold. Parallel pumping system can provide a very high percentage of full flow at low cost compared to the full redundancy alternative (ITT, 2010). Series pumping can reduce costs by using a combination of smaller pumps rather than a single larger pump to accomplish a certain pumping task. This may reduce installation costs as well as operating costs. Series pumping using two or more smaller pumps to handle the total pumping requirement will also provide a high degree of standby capacity. The standby percentage will generally be a high percentage of total system requirements (ITT, 2010). Domestic water pressure booster systems in modern tall buildings, often benefit from combination series-parallel variable speed pumping. The maximum production of parallel and serial centrifugal pumps connection system is possible by ensuring minimum shutdown and breakdowns to increase the availability of pumps (Mohammadi et al., 2016). The connection of centrifugal pumps in the form of parallel and series are illustrated in Figure 1.

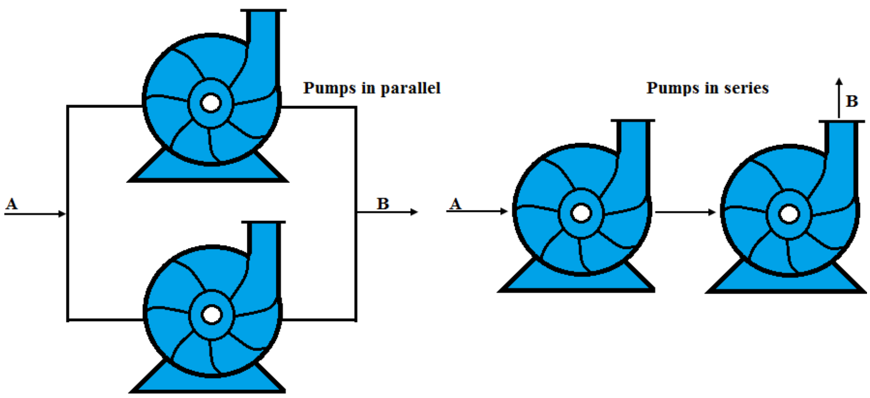

Fig. 1. Connection system of parallel and series pumps.

The instrument we have used for the experiment was produced by Edibon Company. The experiment has been done in Kabul Polytechnic University, the structure of the series pumps are made separately, not as a two-stage pump system.

The parallel and series centrifugal pumps are utilised for mining dewatering process from deep wells and groundwater of mining. Open groundwater dewatering technique is the simplest mine dewatering techniques approach, with potentially the lowest capital costs. The method involves allowing groundwater to enter the pit, then directing it to pumps, from where it is pumped away to the surface. The drawback with this approach is that water levels cannot easily be lowered in advance of mining. Hence there will always be water and wet areas within the base of the pit, which can constrain the choices of mining methods and reduce operational efficiency. There are two key advantages to these techniques. Firstly, appropriately designed and constructed wells will normally produce clean water with very little suspended solids, thereby reducing water treatment requirements. Secondly, an array of wells can be used as a pre-drainage system to lower groundwater levels in advance of mining and to maintain groundwater levels below the base of an open well (GWE, 2013). In some cases, the need to transfer water reveres in mining operations in the high mountains increasingly rely on water being pumped up from sea level for their process needs (Maron, 2014). Mining water can be extremely acidic and leaches or dissolves the rock ore minerals more intensively than common surface or underground water (Geldová, 2000). Mine dewatering is the removal of percolated or logged water from mines to ensure the safety of operating personnel and to safeguard the machinery involved in excavation (Kumar et al., 2013). In an open well mining application, the types of mine dewatering centrifugal pumps one may require to complete the job successfully are high volume pumps for short horizontal discharge, medium head and high head, in both diesel and electric powered centrifugal configurations (Aquatech, 2016). At present, mine dewatering process takes an important place in the range of extracting mine products for open pit mines (Tyulenev, 2017). During the dewatering process of mining, it is necessary to monitor and control the process and detect possible errors caused reduce device reliability (Božek, 2014). For deeper open pits, higher discharge heads are achieved by arranging pumps in series. When two pumps are arranged in serial, their resulting pump performance curve is obtained by adding their heads at the same flow rate as indicated in Figure 2.

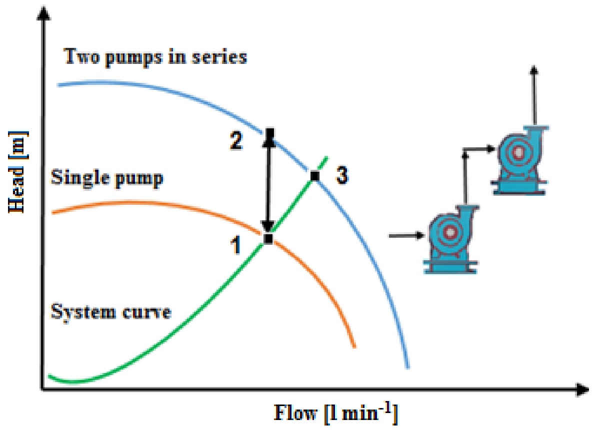

Fig. 2. Performance curves of series pumps arrangement.

Centrifugal pumps in series are used to overcome larger system head loss then one pump can handle alone. For two identical pumps in series, the head will be twice the head of a single pump at the same flow rate. With constant flow rate the combined head moves from 1 to 2. In practice, the combined head and flow rated moved along the system curve to 3 (Orhan, 2012).

Higher flow rates can be achieved with multiple units in parallel. When two or more pumps are arranged in parallel, their resulting performance curves are obtained by adding their flow rates at the same head as indicated in Figure 3.

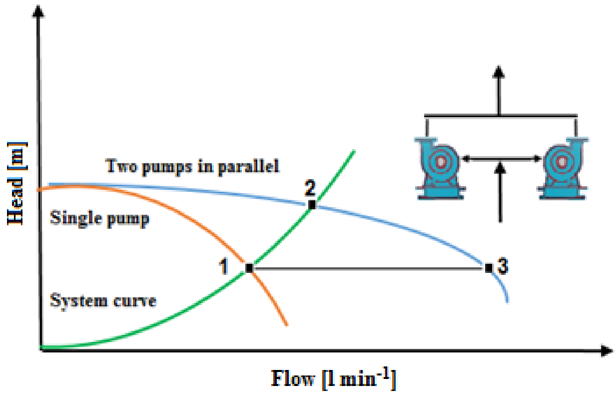

Fig. 3. Performance curves of parallel pumps arrangement.

From the experimental methodology point of view, the connection configuration of devices in parallel and serial form have arranged manually for both Figure 2 and Figure 3. Centrifugal pumps in parallel are used to overcome larger volume flows than one pump can handle alone. For two identical pumps in parallel, the flow rate will double (moving from 1 to 2) compared to a single pump if the head is kept constant. In practice, the combined head and volume flow move along the system curve as indicated from 1 to 3. If one of the pumps in parallel or series stops, the operation point moves along the system resistance curve from point 3 to point 1 – the head and flow rate are decreased (*Orhan, 2012*).

Applied formulas and the pump's characteristics assessment

A brief description of centrifugal pumps characteristics such as head, net position suction head, power, efficiency, and similarity laws are given below:

The characteristic of this device is the guidance required to provide the delivery head, which is necessary for delivering the fluid against of linear resistance in the piping system.

$$H = \frac{P_2 - P_1}{\rho g} \tag{1}$$

Where ρ is fluid density, g is the acceleration of gravity, P_1 and P_2 shows the pressure drop at the beginning and the end of the pump.

The power supplied to fluid generates liquid energy per unit of volume.

Therefore, the power association is between the mechanical energy conversion of the pump and the liquid inside into pump.

The delivery of power to liquid is expressed by hydraulic power or output power P_w:

$$P_w = \rho g Q H \tag{2}$$

Where ρ is fluid density, g is the acceleration due gravity, H is the head, and Q is the flow rate of the liquid.

The mechanical power P_f supplied by the motor to pump, called control power, input power and can be calculated:

$$P_f = \omega\, T = \frac{2\pi}{60}\, nT \tag{3}$$

Where n is the frequency of rotation [rpm] (rpm, revolutions per minute), T is torque [Nm], ω is angular axis speed in [rad sec^{-1}] (*Edibon, 2014*).

The pump efficiency η is defined as the ratio of power supplied to the liquid and the power supplied to drive the pump.

$$\eta = \frac{P_w}{P_f} = \frac{\rho g Q H}{\frac{2\pi}{60} nT} \tag{4}$$

Where ρ is fluid density, g is the acceleration due gravity, P_f is mechanical power, P_w is hydraulic power. If there are no losses, $P_w = P_f$, and the efficiency is 100 %, but it is not the case in operation.

Required net position suction head ($NPSH_R$) is a function of the pump, and it is defined as follows:

$$NPSH_R = \left(\frac{P_1}{\rho g} + \frac{w_1^2}{2g} - \frac{P^*}{\rho g}\right) \quad (5)$$

Where P^* is the transported liquid's steam, P_1 is pressure and w_1 is the velocity of liquid inside the pump.

$$w = \frac{Q}{A} \quad (6)$$

Where A, [m^2] is the circular surface area of the impeller which is calculated as:

$$A = \frac{\pi}{4} D^2 \quad (7)$$

Where D [m] is impeller diameter.

Similarity laws represent the mathematical relationship between variables that are related to pump performance:

$$Q = \left(\frac{n}{n_n}\right) Q_n \quad (8)$$

$$H = \left(\frac{n}{n_n}\right)^2 H_n \quad (9)$$

$$P = \left(\frac{n}{n_n}\right)^3 P_n \quad (10)$$

$$NPSH_R = \left(\frac{n}{n_n}\right)^2 NPSH_{Rn} \quad (11)$$

Where n is the current frequency of revolution in [rpm] of the pump and subscript n denotes the functioning value at the nominal speed pump (Karassik, 1998).

Procedure of experiments

During investigation, the computer controlled multi-pumps of series and parallel are used, the computer technology and digitisation are now commonplace in every social sphere, touching our everyday lives (Rybar, 2017).

The investigation of experiment has been done in Kabul Polytechnic University for centrifugal pumps which were manufactured by Edibon Company.

This instrument allows checking the reliability of serial and parallel centrifugal pumps at different speeds of rotation.

Through testing of experimentation, both centrifugal pumps are connected in series and parallel form. We set the frequency of rotation in 3000 [r.p.m], for this turning speed we write the flow Q evacuated by the pumps, both section pressures, inlet pressure P_1 and discharge pressures P_2, as well the torque, T [Nm]. Then, we fix a new frequency of rotation to measure the flow Q evacuated by the pumps, both section P_1 and discharge P_2 pressures and the torque, T [Nm] to obtain the average values of measured data.

We also controlled the change of flow in four steps of valve changing to obtain new data information for different speeds of rotation (2200, 2600, 2800 and 3000 [r.p.m]).

The data of Q, P_1, P_2 and T at a different rotation of speed for series centrifugal pumps are shown in Table 1.

Tab. 1. Experiment data of two series centrifugal pumps.

n = 3000 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	18.23	16.92	13.55	7.8	4.61
	***P*₁** [bar]	-0.03	-0.03	-0.02	-0.01	-0.01
	***P*₂** [bar]	1.21	1.46	1.89	2.28	2.31
	T [Nm]	0.37	0.45	0.59	0.71	0.72
n = 2800 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	17.52	15.34	14.45	11.45	6.44
	***P*₁** [bar]	-0.02	-0.02	-0.02	-0.01	-0.01
	***P*₂** [bar]	1.31	1.52	1.55	1.91	2.06
	T [Nm]	0.4	0.47	0.48	0.59	0.64
n = 2600 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	16.91	15.45	12.02	8.19	5.45
	***P*₁** [bar]	-0.03	-0.02	-0.01	-0.01	-0.01
	***P*₂** [bar]	0.95	1.4	1.77	1.9	2
	T [Nm]	0.29	0.43	0.55	0.59	0.62
n = 2200 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	16.53	14.82	10.98	8.23	4.28
	***P*₁** [bar]	-0.03	-0.02	-0.02	-0.01	-0.01
	***P*₂** [bar]	0.8	1.06	1.59	1.68	1.7
	T [Nm]	0.24	0.33	0.49	0.52	0.53

In similar circumstances, we received new data during of experiment Q, P_1, P_2 and T at a different rotation of speeds (2200, 2600. 2800 and 3000 [r.p.m]) for parallel centrifugal pumps that are shown in Table 2.

Tab. 2. Experiment data of two parallel centrifugal pumps.

n = 3000 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	28.77	26.84	24.37	21.27	17
	***P*₁** [bar]	-0.02	-0.02	-0.02	-0.01	-0.01
	***P*₂** [bar]	0.83	0.84	0.86	0.87	0.88
	T [Nm]	0.26	0.27	0.28	0.29	0.3
n = 2800 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	27.97	23.13	18.77	12.55	6.11
	***P*₁** [bar]	-0.02	-0.02	-0.01	-0.01	-0.01
	***P*₂** [bar]	0.83	0.86	0.89	0.91	0.96
	T [Nm]	0.25	0.26	0.27	0.28	0.29
n = 2600 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	26.16	21.08	15.27	8.82	4.51
	***P*₁** [bar]	-0.02	-0.01	-0.01	-0.01	-0.01
	***P*₂** [bar]	0.82	0.85	0.87	0.9	0.94
	T [Nm]	0.24	0.25	0.26	0.28	0.29
n = 2200 [r.p.m]	**Number**	**1**	**2**	**3**	**4**	**5**
	Q [l min^{-1}]	24.01	17.21	12.05	8.67	3.9
	***P*₁** [bar]	-0.01	-0.01	-0.01	-0.01	-0.01
	***P*₂** [bar]	0.8	0.83	0.91	0.93	0.96
	T [Nm]	0.24	0.25	0.26	0.28	0.29

Results

From the perspective of comparison and reliability, this study explains the effect of different frequencies of rotation DFR on the employment of two centrifugal pumps in serial and parallel system. The results show that the VSD and DFR of serial and parallel centrifugal pumps can be determined by using the principles of energy efficiency, the limitations of this operating range are strongly dependent on the rotation speed of the pump. The measurement values computed only for four steps of DFR (2200, 2600, 2800, and 3000 [r.p.m]). Table 3 indicates the series pumps configuration results at 3000 [r.p.m]. For each current flow Q in Table 3, calculated the hydraulic power P_w, mechanical power P_f, pump efficiency η, H-head, and $NPSH_R$ using equations (1, 2, 3, 4, 5, and 6). The pumps and system curves in Figure 4, which depends to series pumps, and the Figure 5, which relates to parallel pumps, indicates reduce of efficiency in four steps of different rotating speeds (2200, 2600, 2800 and 3000 rpm) that have undesirable effects on pump's reliability, particularly when pump efforts at 2200 rpm or slow revolutions per minute..

Correspondingly in Table 4, the similar measurement procedure for rotational frequency sets of parallel joining have been done, and the mechanical power P_f, hydraulic power P_w, head H, the efficiency of pump η and $NPSH_R$ calculated for (2200, 2600, 2800 and 3000 rpm).

The affinity laws outcomes for series and parallel pumps in Table 5 and Table 6 (that can be used to estimate the effect of fluid change, efficiency, speed, or size of any dynamic pump) are calculated via using equations (8, 9, 10, and 11), and using measured values of Table 3 and Table 4 for series and parallel pumps separately.

The pump efficiency is usually estimated directly relate to rotational speed, therefore the efficiency curves and pump curves followed the similarity laws using equations (8) and (9). When the pump is driven outside from the operating area, the pump efficiency reduced and may be susceptible to unsafe effects.

As a result for dewatering mining process, a higher flow rates can be achieved with parallel pumps connection, and the series pump connection are used to overcome larger volume. Even though the research was carried out on small and low productive capacity centrifugal pumps in the laboratory of Kabul Polytechnic University but the study will consider requirements for centrifugal pumps connection in the serial and parallel form in mine dewatering process. The advantage of pumps connection in parallel and serial configuration guarantee quality, durability and deliver maximum performance at minimum cost. Centrifugal pump in series is used to overcome larger system head loss. Therefore, for two identical pumps in series, the head will be twice to transfer liquid to a high height, for instance, for 800 [m] we could connect more than two pumps in a series configuration, this should be noted that the transfer of liquids to high head depended to the capacity of the pump. In an open source mining application, the dewatering pumps we may require to overcome the job successfully by parallel pumps for short horizontal discharge, medium head and high head to 700 [m] series centrifugal configurations are useful. When two or more pumps are arranged in parallel form caused to overcome larger volume flows than one pump. Through the experimental investigation, the head capacity can be increased by connecting more pumps in series, or the flow rate capacity can be increased by connecting more pumps in parallel. If we require a heavy duty to transfer dirty water, wastewater or slurries dredging pumps can be used.

Tab. 3. Calculated experimental values for two series centrifugal pumps.

***n* = 3000 [r.p.m]**					
Number	**1**	**2**	**3**	**4**	5
Q [l min^{-1}]	18.23	16.92	13.55	7.8	4.61
H [m]	12.67	15.22	19.51	23.39	23.70
$\boldsymbol{P_W}$ [W]	37.67	42.01	43.13	29.77	17.82
$\boldsymbol{P_f}$ [W]	116.23	141.37	185.35	223.0	226.2
$\boldsymbol{\eta}$ [%]	32.41	29.72	23.27	13.34	7.88
w [m s^{-1}]	0.42	0.39	0.31	0.18	0.10
$\mathbf{NPSH_R}$ [m]	0.29	0.16	-0.008	-0.24	-0.34
n = 2800 [r.p.m]					
Number	**1**	**2**	**3**	**4**	**5**
Q [l min^{-1}]	17.52	15.34	14.45	11.45	6.44
H [m]	13.59	15.73	16.04	19.61	21.15
$\boldsymbol{P_W}$ [W]	38.83	39.37	37.81	36.64	22.21
$\boldsymbol{P_f}$ [W]	117.28	137.81	140.74	172.9	187.6
$\boldsymbol{\eta}$ [%]	33.11	28.57	26.86	21.17	11.83
w [m s^{-1}]	0.41	0.361	0.34	0.26	0.15
$\mathbf{NPSH_R}$ [m]	0.32	0.13	0.06	-0.04	-0.29
n = 2600 [r.p.m]					
Number	**1**	**2**	**3**	**4**	**5**
Q [l min^{-1}]	16.91	15.45	12.02	8.19	5.45
H [m]	10.01	14.50	18.18	19.51	20.53
$\boldsymbol{P_W}$ [W]	27.61	36.56	35.65	26.07	18.25
$\boldsymbol{P_f}$ [W]	78.95	117.07	149.74	160.6	168.8
H [%]	34.97	31.23	23.81	16.22	10.81
w [m s^{-1}]	0.39	0.36	0.28	0.19	0.12
$\mathbf{NPSH_R}$ [m]	0.16	0.14	-0.01	-0.22	-0.32
n = 2200 [r.p.m]					
Number	**1**	**2**	**3**	**4**	**5**
Q [l min^{-1}]	16.53	14.82	10.98	8.23	4.28
H [m]	8.48	11.03	16.45	17.26	17.47
$\boldsymbol{P_W}$ [W]	22.86	26.67	29.46	23.18	12.19
$\boldsymbol{P_f}$ [W]	55.29	76.02	112.88	119.8	122.1
$\boldsymbol{\eta}$ [%]	41.35	35.08	26.09	19.34	9.98
w [m s^{-1}]	0.38	0.34	0.25	0.19	0.10
$\mathbf{NPSH_R}$ [m]	0.13	0.08	-0.18	-0.22	-0.35

Calculating characteristics of centrifugal pumps according to equations and tables data shows that the rotational speed, torque, power, shaft, and efficiency affects the reliability of the pump.

The workout and calculation of serial and parallel centrifuge pumps characteristics according to the mentioned equations are as follows:

At the start of the experiment, we write the experimental data. At first, we measured the water temperature at the begging of test t_1 = 21 [°C] and then at the end of test t_2 = 23 [°C]. Eventually, we obtain the average temperature of water t_{av}= 22 [°C].

Regarding the average temperature, gravity acceleration and water density from physical properties of the table have been selected 9.81 [m s^{-1}] and 997.9 [kg m^{-3}] correspondingly, then calculated each value only for four steps of speed revolutions (2200, 2600, 2800 and 3000 [rpm]).

At 3000 [rpm], for current Q measured each value in Table 3, for example, power output, power input, pumping efficiency, liquid velocity, head H, and $NPSH_R$, using Equations (1, 2, 3,4, 5 and 6). For the circular surface area, we use Equation (7). All measured values for 3000 [r.p.m.] are shown in Table 3; similar measurement procedure was performed for a different rotating frequency set (2800, 2600 and 2200 [r.p.m.]) too. The measured values for two centrifuge pumps in series configuration are shown in Table 3.

Centrifugal pumps are over and over again controlled by adjusting their speed, which affects the flow of pump and output pressure. Many pumping systems require a change in flow or pressure. To get a different operating point either system curve or pump curve must be changed.

Preferably, the pump operates in its best efficiency point BEP, if the pump operates out of operating area, the pump efficiency decreases and may be susceptible to damaging effects.

For two series coupling of centrifugal pumps, the pump and system curves at different rotation speed are shown in Figure 4.

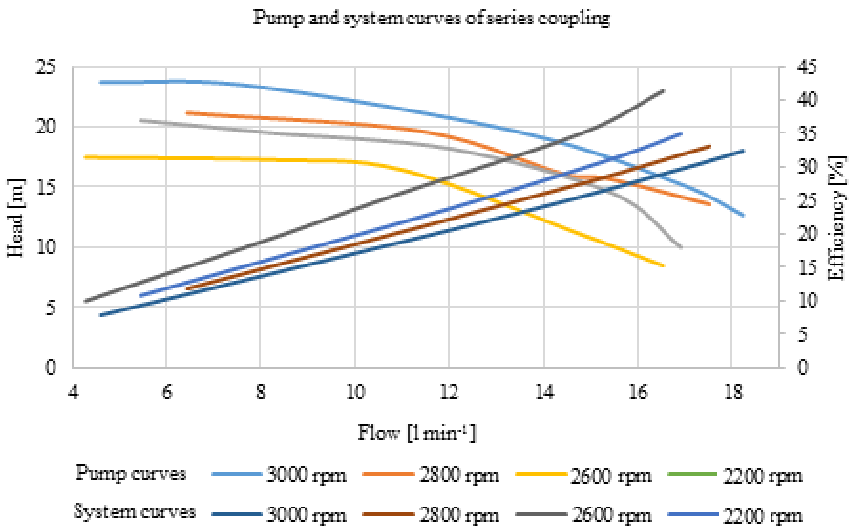

Fig. 4. The series pumps system and pump curves shape when these pumps are driven at different rotational speeds.

For each flow Q, the values of output power, input power, the velocity of liquid, efficiency, head, and $NPSH_R$ were calculated and are given in Table 4 for (2200, 2600. 2800 and 3000 rpm) independently. Measured values for two parallel centrifugal pumps are shown in Table 4.

Tab. 4 Calculated experimental values for two parallel centrifugal pumps

n = 3000 [r.p.m]					
Number	**1**	**2**	**3**	**4**	**5**
Q [l min^{-1}]	28.77	26.84	24.37	21.27	17
H [m]	8.68	8.78	8.99	8.99	9.09
P_w [W]	40.75	38.47	35.74	31.19	25.21
P_f [W]	81.68	84.82	87.96	91.10	94.24
η [%]	49.89	45.35	40.63	34.24	26.75
w [m s^{-1}]	0.67	0.63	0.57	0.50	0.40
$NPSH_R$ [m]	1.74	1.45	1.11	0.82	0.38
n = 2800 [r.p.m]					
Number	**1**	**2**	**3**	**4**	**5**
Q [l min^{-1}]	27.97	23.13	18.77	12.55	6.11
H [m]	8.68	8.99	9.19	9.40	9.91
P_w [W]	39.62	33.92	28.15	19.24	9.87
P_f [W]	73.30	76.23	79.16	82.10	85.03
η [%]	54.05	44.49	35.56	23.43	11.61
w [m s^{-1}]	0.65	0.54	0.44	0.29	0.14
$NPSH_R$ [m]	1.62	0.94	0.55	0.02	-0.30
n = 2600 [r.p.m]					
Number	**1**	**2**	**3**	**4**	**5**
Q [l min^{-1}]	26.16	21.08	15.27	8.82	4.51
H [m]	8.58	8.78	8.99	9.29	9.70
P_w [W]	36.62	30.21	22.39	13.37	7.14
P_f [W]	65.34	68.06	70.79	76.23	78.95
η [%]	56.04	44.38	31.63	17.54	9.04
w [m s^{-1}]	0.61	0.49	0.36	0.20	0.10
$NPSH_R$ [m]	1.35	0.80	0.22	-0.19	-0.35
n = 2200 [r.p.m]					
Number	**1**	**2**	**3**	**4**	**5**
Q [l min^{-1}]	24.01	17.21	12.05	8.67	3.9
H [m]	8.27	8.58	9.40	9.60	9.91
P_w [W]	32.41	24.09	18.47	13.58	6.30
P_f [W]	55.29	57.59	59.89	64.50	66.81
η [%]	58.62	41.83	30.84	21.05	9.43
w [m s^{-1}]	0.56	0.40	0.28	0.20	0.09
$NPSH_R$ [m]	1.16	0.40	-0.01	-0.20	-0.36

Preferably for VSD pump in four steps, the system curves consists mainly dynamic head, and pump usually works at best efficiency point BEP. If the system curve has a significant portion of the static head, changing the rotational speed can change the point of operation.

Figure 5 is completed from data of Table 4 by making the all pump and efficiency curves. Efficiency decreases affected pumps reliability, the resulting operating point locations with four different system curve shapes are given in Figure 5.

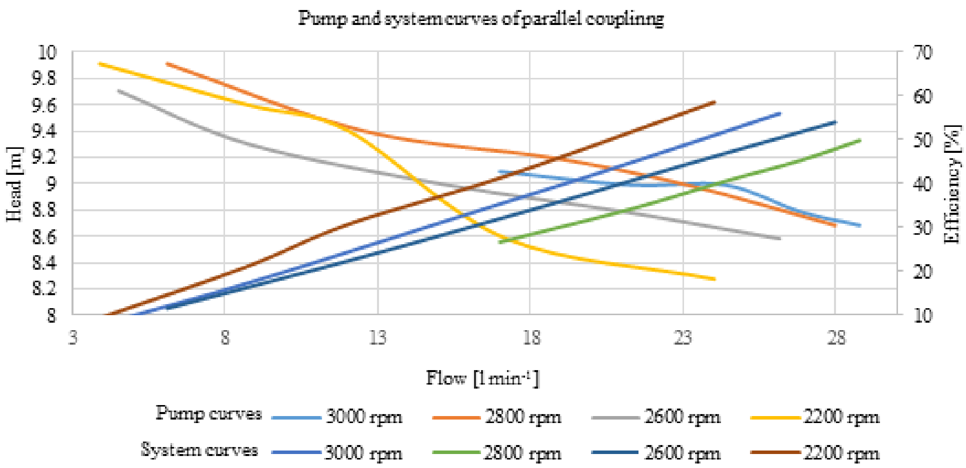

Fig. 5. The Parallel pumps system and pump curves shape at different rotational speeds.

In addition, the figures report the estimated decrease of the pump characteristic life as a function of relative flow rate and adverse events that may occur if centrifugal pumps are driven outside its recommendable operating region at fixed speed.

The similarity laws are calculated using equations (10, 11, 12 and 13), experimental data are calculated for parallel and serial centrifugal pumps given in Table 5 and Table 6, which can be used to estimate the effect of the fluid change, Efficiency, speed or size of any turbo-dynamic device.

Tab. 5. The similarity rules of two parallel coupling centrifugal pumps.

$\boldsymbol{n}$ [r.p.m]	$\boldsymbol{Q}_\mathbf{n}$ [l min^{-1}]	$\boldsymbol{H}_\mathbf{n}$ [m]	$\boldsymbol{P}_\mathbf{fn}$ [W]	**NSPH**$_{\mathbf{Rn}}$ [m]
2	26.85	7.56	66.41	1.52
3	25.97	7.48	58.69	1.40
4	22.13	6.14	39.58	0.97

Tab. 6. The similarity rules of two series coupling centrifugal pumps.

$\boldsymbol{n}$ [r min^{-1}]	$\boldsymbol{Q}_\mathbf{n}$ [l min^{-1}]	$\boldsymbol{H}_\mathbf{n}$ [m]	$\boldsymbol{P}_\mathbf{fn}$ [W]	**NSPH**$_{\mathbf{Rn}}$ [m]
2	17.01	11.03	94.50	0.25
3	16.26	11.71	93.90	0.14
4	14.30	7.16	47.83	0.12

The net position suction head requires $NPSH_R$ a minimum level, so $NPSH_R$ does not tend to reach zero at very low speeds. The issue of this paper which is done experimentally, (reliability of parallel and serial centrifugal pumps for dewatering in mining process) represents the issue to find the solution of subject and problems related to centrifugal pumps reliability for dewatering of mining process (Černecký, 2015).

Conclusion and summary

This article represented, the current flow control function tested with (*QH*) curve, based on the pump flow estimate. This study was considered for the management of control strategy that includes efficient operation as well as avoiding the conditions that can reduce the reliability of pumps.

This research focused on series and parallel pumping systems which operate to achieve a wide range of flow for mining process, to determine the energy efficient control strategies for VSD controlled pumping systems by applying on three main research areas. The first part of the procedure is evaluated with suitable operating conditions for VSD by controlled coupling pumping connection system. The second part of the application considers the main flow monitoring capabilities for each parallel and serial pumps. The third application area, the method of implementation energy control, to save a VSD control for serial and parallel pumping system.

The accuracy of the used (series and parallel) pumps operation point estimation methods were evaluated to be sufficient for the presented sub-optimisation of VSD controlled pumps. As well, the specific energy consumption of the serial with parallel pumping system could be optimised with the individual pump system. More results of realising energy savings in real life of coupling pumping systems could be gathered with simulated and experimental system situations. Especially case examples for pumping systems serial and parallel pumping units would give interesting information of the benefits of the proposed strategy (mining process). This study was carried out for the estimation of the pump model operating point position, which can be performed by a frequency converter. The pump curve $Q = f(H)$ and the system curve $\eta = f(Q)$ based methods are calculated. For maximum efficiency on $\eta = f(Q)$, curve we will calculate the annual power consumption of serial and parallel pumps according to pumps operating hours per year.

Application of these methods was evaluated by laboratory measurements with serial and parallel centrifugal pumps. The results showed that application of the model-based method for estimating performance points was measured. Future research about serial and parallel pumps will be on a flow recirculation for dewatering of mining process.

Using the characteristics of functional curves, head performance curves, flow rate, efficiency, mechanical power, hydraulic power, velocity, the position of the suction head, reliability analysis of two pumps based on performance curve of, and the recommended operating range of the VSD are studied.

Parallel and serial pumps can also measure pump flow, to determine the actual operating point location of centrifugal pumps.

In addition, production critical applications can be equipped with backup pumps that are started if the operating pumps fail. However in practice, the major part of series and parallel pumping systems may only have a motor phase current, and a process related measurement, which do not directly indicate the operational efficiency, hydraulically and mechanical reliability of the pumps. Nowadays, there are numerous condition and efficiency monitoring products available for coupling pumping systems, generally considered as an energy efficient control approach, the actual operating point locations of a VSD pump may well be found in regions with a lower pump efficiency and higher risk for a mechanical failure of the pump, which may remain undetected by visual check-ups. As a result, the issue of the study was the reliability of a centrifugal pump at different rotational speeds and flow rates. The use of common energy efficiency and reliability based criteria the determination of the recommendable operating region of a VSD coupling centrifugal pumps were investigated.

The monitoring of series and parallel centrifugal pumps operation utilising the information available from a frequency converter. The variable-speed-driven of coupling centrifugal pumps are widely used in mining process applications, and often the coupling pumps may be driven in adverse operating conditions, which can lead to increase the energy and maintenance costs for the connected pumping system. Although the research focuses on series and parallel centrifugal pumps, the tested properties, can also be used for other types of centrifuge pumps such as gear pumps, peripheral and axial pumps.

Acknowledgements*: This paper was prepared within the work on a research project KEGA MŠ SR 003TU Z-4/2016: Research and education laboratory for robotics and RFBR research project No 18-08-00772 A. Also this work was done as a result of the project SAMRS/2013/ of the Slovak official development assistance supporting the cooperation between the Slovak University of Technology in Bratislava (STU) and the Kabul Polytechnic University (KPU) in Afghanistan.*

References

Aquatech. (2016). The real value of the pumps selected is in the support that comes with them. Canada. http://www.aquatechdewatering.com/cmsAdmin/uploads/news/pdf/Mine-Dewatering-editorial.pdf

Božek, P. (2013). Robot path optimization for spot welding applications in automotive industry. *Tehnički vjesnik*, 20.

Božek, P. (2014). Automated Detection Type Body and Shape Deformation for Robotic Welding Line. *Advances in Systems Science, Advances in Intelligent Systems and Computing*. 240.

Božek, P. (2014). Control of a robotic arm on the principle of separate decision of an inertial navigation system. *Applied Mechanics and Materials*, 611.

Brodnianska, Z., Cernecky, J. (2016). The impact of the shaped vertical heated surfaces on the values of the heat transfer coefficients. *JP Journal of Heat and Mass Transfer. Volume 13, Number 4, ISSN: 0973-5763*

Černecký, J., Božek, P., Pivarčiová, E. (2015). A new system for measuring the deflection of the beam with the support of digital holographic interferometry. *Electrical Engineering*, 66 (1).

Edibon. (2014). Technical Teaching Equipment. Computer Controlled Multi pump Testing Bench with SCADA. Spain.

Erickson, R. B., Sabini E. P., Stavale A. E. (2000). Hydraulic Selection to Minimize the Unscheduled Maintenance Portion of Life Cycle Cost, Karlsruhe, Germany. In Proceedings of Pump Users International Forum.

Geldová, E. (2000). Acidification of water in the bearing area. Košice. *Acta Montanistica Slovaca*, 5(3).

Kumar, N., Sarkar, S., Paul, B. (2013). Review on Dewatering Pumping Network for Underground Coal Mine. India. http://www.inacomm2013.ammindia.org/Papers/137-inacomm2013_submission_212.pdf

Karassik, I. J., Mcguire, T. (1998). Centrifugal Pumps, second edition. Chapman & Hall, New York, USA.

Kimberly, F. Bernadette, P. Drew, W. Schiller, M. Smith, B. (2002). Understand the basics of centrifugal pump operation.

ITT. (2010). Parallel and Series Pump Application. Austin Avenue Morton Grove. www.bellgossett.com

Larralde, E., Ocampo, R. (2010). Centrifugal pump selection process: a real example. *World Pumps*, 3. http://csmres.co.uk/cs.public.upd/article-downloads/Pump-selection---a-real-example.pdf

Mohammadi, M., Piyush, R., Suprakash, G. (2016). Improving productivity of dragline through enhancement of reliability, inherent availability and maintainability. *Acta Montanistica Slovaca*, 21(1).

Maron, R., Zuzunaga, A. (2014). Efficiency of pumps in parallel operation on long-distance water pipelines. *BI0528*. https://www.cidra.com/sites/default/files/document_library/BI0528_WIM_2014_Article-FINAL.pdf

Orhan, M. (2012). Pumping. Marmara University Departments of Information Technology. Turkey. http://mimoza.marmara.edu.tr/~orhan.gokyay/enve311/ch7.pdf

Qazizada, M. E., Sviatskii, V., & Božek, P. (2016). Analysis performance characteristics of centrifugal pump. *MM Science journal*, 2016(10).

Rybár, P., Hvizdák, L., Hronček, P., Jesenský, M., Šimůnek, R. (2017). Computer modelling as a basic research and visualisation tool to research defunct historical mining technologies, using the example of cementation water mining in Smolník (Slovakia). *Acta Montanistica Slovaca*, 22 (3).

Singh, D., & Suhane, A. (2013). Study of Centrifugal Pump Using Failure Mode Effect and Critical Analysis Based on Fuzzy Cost Estimation. *International Journal of Science and Research,* 4(7).

Stojiljkovic, E., Grozdanovic, M., & Marjanovic, D. (2014). Impact of the underground coal mining on the environment. *Acta Montanistica Slovaca,* 19(1).

Švandová M., Raschman P., Doráková A., Fedoročková A., Sučik G (2016). Testing of potential reactive materials for removal of heavy metals from contaminated water. Slovakia. *Acta Montanistica Slovaca,* 21(2).

Sviatskii, V., Repko, A., Janačova, D., Ivandič, Ž., Perminova, O., Yury Nikitin. (2016). Regeneration of a fibrous sorbent based on a centrifugal process for environmental geology of oil and groundwater degradation. *Acta Montanistica Slovaca,* 21(4).

Groundwater Engineering (GWE). (2013). Mine Dewatering. United Kingdom. www.groundwaterinternational.com

Sivakumara, M., Ramezanianpourb, M., & O'Halloran, G. (2013). Mine Water Treatment Using a Vacuum Membrane Distillation System. Dubai. http://ro.uow.edu.au/cgi/viewcontent.cgi?article=3438&context=eispapers

Truflo. (2017). Underground Dewatering Pumps. Bathurst Australia. http://www.truflopumps.com.au

Viholainen, J., Kortelainen, J., Ahonen, T., Aranto, N., Vakkilainen, E. (2009). Energy Efficiency in Variable Speed Drive (VSD) Controlled Parallel Pumping. France. In Proceedings of the 6th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS '09). Nantes.

Tyulenev, M., Litvin, O., Cehlár, M., Zhironkin, S., Gasanov, M. (2017). Estimation of Hydraulic Backhoes Productivity for Overburden Removing at Kuzbass Open Pits. Russia. *Acta Montanistica Slovaca*, 22(3).

Verhoeven, R., Willems, E., Harcouët-Menou, V., De Boever, E., Hiddes, L. Op 't Veld, P., Demollin, E. (2014). Minewater 2.0 project in Heerlen the Netherlands: transformation of a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure for heating and cooling. Heerlen. http://www.mijnwater.com/wp-content/uploads/2014/04/Energy-procedia_IRES-2013_Verhoeven-V20012013-Final-1.pdf

Xylem. (2013). Let's Solve Water. United States. www.xyleminc.com