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Development of Virtual Laboratory for the Study of Centrifugal Pump Cavitation and Performance in a Pipeline Network

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Abstract. The conventional method of conducting laboratory experiments in engineering becomes a serious challenge asa result of the COVID-19 pandemic; the development of a virtual laboratory is considered a suitable substitute to real laboratory. In this work, a virtual laboratory for a family of centrifugal pumps has been developed. Cavitation development within the centrifugal pumps and the pumps performances in pipeline networks were studied. Negative potential head and high fluid temperature increased early cavitation incidence, while low fluid temperature, as well as positive potential head reduced it. The choice of pipe diameter and its roughness factor played significant roles in the pumps' performance. The study shows that virtual laboratory represents a good training environment that enables precise pipeline and pump flow matching.

Keywords: Cavitation; Covid-19 pandemic; Pipeline network efficiency; Pump; Virtualexperiments

1. Introduction

The current COVID-19 pandemic, declared as an outbreak of Public Health Emergency of International Concern by the World Health Organization in January 2020 (Harapana et al., 2020) and identified as a pandemic in March 2020 (Gennaro et al., 2020) is posing an enormous threat to the conduct of reallife laboratory experiments.

In combatting the global lockdown attributed to the COVID-19 pandemic, there is a need to explore new alternatives to academic delivery, and the virtual class mode is a promising way forward (Evans et al., 2020; Arora and Srinivasan, 2020). In a recent publication,Salmerón-Manzano and Manzano-Agugliaro (2018) observed that "bibliographic analysis confirms that research in virtual laboratories is a very active field, where scientific productivity has exponentially increased over recent years in tandem

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with universities growth”. In studies conducted by Ari-Gur et al. (2015) and Boonbrahm et al. (2019), their findings showed that virtual laboratories have the potential to enhance learning practical-oriented courses and minimize the procurement cost of laboratory equipment.

In many developing countries, the practical experience required by students of science and engineering to fully understand theoretical aspects of their courses are inadequate. A pragmatic approach to solving this problem is to develop a computer-simulated virtual laboratory to complement existing laboratories to improve the identified problems. While it is capital-intensive to set up real laboratories that investigate varieties of flow parameter dependences, a virtual laboratory for flow pipe networks is simple and cost-effective, particularly in developing countries experiencing economic challenges. The virtual laboratory makes sure that its resources are available to each student, unlike in a real laboratory where students form groups to perform an experiment. Therefore, the objective of this work was to leverage on he benefits of a virtual laboratory to develop a fluid mechanics virtual laboratory that investigates centrifugal pump cavitation and performance in a pipe network.

This area of development was chosen because of the cavitation phenomenon menace: on pump casing and impeller. Cavitation always affects flow assurance in the manufacturing, food processing, and oil industries. The menace is characterized by leakages and loss of pressure in pumps and other related hydraulic components (Binama et al., 2016; Luo et al., 2016). However, the cavitation phenomenon still has some benefits elsewhere, including the treatment of stabilized leachate in municipal landfills (Moersidik et al., 2021) and the disinfection of *Escherichia coli b*acteria using hydrodynamic cavitation (Eva and Indika, 2013). It should be noted that one of the benefits of a virtual laboratory is that it requires a relatively small power supply to operate computer systems. Hence, experiments can be conducted regularly in virtual laboratories. In addition, most of the laboratory equipment required to teach some fundamental science and engineering principles are not readily available in the appropriate quantities and qualities due to poor economies and other social factors in developing countries. The economic benefit of this study is that different experimental rigs can be virtually formulated without incurring significant costs, in contrast to real laboratories, where such exercises are impossible without extra costs. This work on virtual laboratories will provide engineering students with the requisite practical knowledge that will allow them to be integrated into industries where pumps and piping systems are used.

2. Virtual Package Developmental Procedure

A family of centrifugal pumps were studied. The flow energy of a fluid is given by equation (1). This energy is constant from one section to another, according to the law of conservation of energy under ideal conditions,

$$E = \frac{P}{\rho} + \frac{1}{2}v^2 + gz \tag{1}$$

where P is the pressure, v is the flow velocity, g is the acceleration due to gravity, z is the flow elevation head and ρ is the fliud density.

The modification of the equation in terms of the fluid flow head leads to Bernoulli’s equation:

$$H = h + \frac{v^2}{2g} + z \tag{2}$$

where H is the total head of the flow and h is the pressure head.

Due to pressure loss as a result of friction in a pipe, the ideal flow formula in Equations 1 and 2 can be modified to describe real-world examples. For instance, the pressure loss in a pipe under steady flow is obtained from the Darcy-Weisbach equation:

$$\Delta P = \frac{fL}{D}\frac{v^2}{2g} \tag{3}$$

where ΔP is the pressure loss in pipe,f is the pipe friction factor,L is the pipe length and D is the pipe diameter,

The solution of the Darcy friction factor in turbulent flow is obtained from the Moody diagram or by iteratively solving the Colebrook equation. The boundary layer in turbulent pipe flow is thin; thus, the Darcy friction factor depends on the pipe's roughness factor. The Colebrook equation is the most widely used equation to obtain the Darcy friction factor (Kiijarvi, 2011):

$$\frac{1}{\sqrt{f}} = -2.0\,log\left(\frac{\frac{e}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{4}$$

where Re is the flow Reynold's number and e is the pipe roughness factor.

The flow rate of fluid through a pump and its net head are the essential parameters which characterized its performances. The pump net head is defined as the change in the Bernoulli head between the inlet and outlet of the pump (Çengel and Cimbala, 2006). The net head is defined as:

$$H = \left(\frac{P_{out}}{\rho g} + \frac{V_{out}{}^2}{2g} + z_{out}\right) - \left(\frac{P_{in}}{\rho g} + \frac{V_{in}{}^2}{2g} + z_{in}\right) \tag{5}$$

To avoid vibration, noise, and loss of efficiency caused by cavitation in the pump when the stagnation pressure, P, in the pump inlet falls below the vapor pressure, P_v, of the liquid being pumped; P must always be ensured to be greater than P_v. Cavitation is a menace in industrial processes where pumps are used. Generally, if cavitation causes are not properly addressed, cavitation can cause critical damage to the surfaces of pump impeller blades through pitting and erosion of the blades (Çengel and Cimbala, 2006).

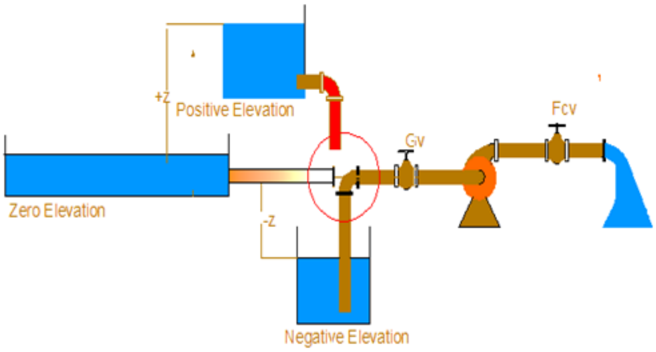


Figure 1 The three respective positions of reservoir are shown at the upstream section of a centrifugal pump

Figure 1 shows the three respective positions of reservoirs at the upstream section of a centrifugal pump: zero elevation, negative elevation, and positive elevation positions. The cavitation incidence is more pronounced in installations that have negative elevations than others. The flow parameter that is always calculated to investigate cavitation is called the net positive suction head (NPSH$_a$), where the suffix "a" means available. It is defined as the difference between the pump stagnation pressure head and the vapor pressure head at the pump inlet:

$$NPSH_a = \left(\frac{P}{\rho g} + \frac{V^2}{2g}\right)_{pump} - \frac{P_v}{\rho g} \tag{6}$$

From Equation 6, cavitation occurs when $NPSHa \leq 0$.

The mechanism of cavitation is graphically depicted in Figure 2 with respect to suction pressure, fluid vapor pressure, and the discharged pressure.

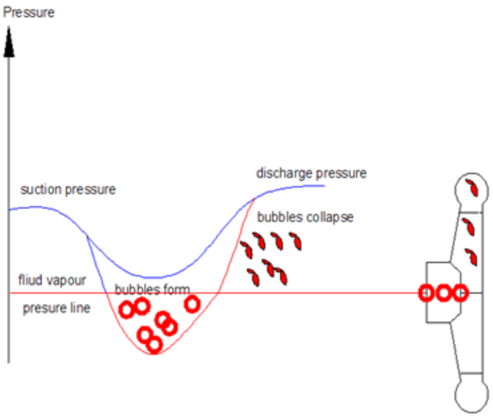


Figure 2 The pressure gradient through a centrifugal pump experiencing normal pumping conditions (blue curve) and that experiencing cavitation (red curve). This image also shows fluid bubble formation and collapse in the pump.

Overtime, the fluid pressure rises as it passes out of the discharge. This phenomenon causes bubbles to collapse within the pump, as shown in Figure 2. The pressure at the pump inlet is determined by the pressure on the fluid surface, and friction losses in the suction pipework and head are due to the reservoir position (Diwakar et al., 2012),

$$NPSH_r = H_A \pm H_z - H_F + H_v - H_{vp} \tag{7}$$

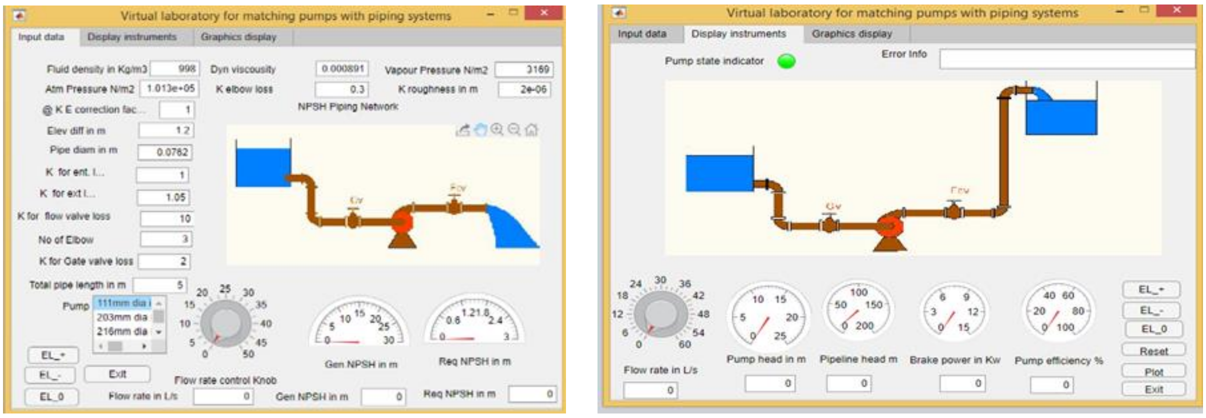
where H_A is absolute pressure on supply tank liquid surface, $H_z$is vertical distance between liquid surface and the pump centre line, H_F is friction losses in the suction piping, $H_v$is velocity head at the pump suction,$H_{vp}$is absolute vapour pressure of the liquid at the pumping temperature and $NPSH_r$ is the net positive suction head required.

The energy equation for a general piping system with an elevation change, major and minor losses, and fluid kinetic energy head change provide the required net head (pump head), H_p, as:

$$H_p = \frac{P_2 - P_1}{\rho} + \frac{\alpha_2 {V_2}^2 - \alpha_1 {V_1}^2}{2g} + (z_2 - z_1) + h_{Lmajor} + h_{L\,min\,or} \tag{8}$$

The considered centrifugal pumps were made up of the same casing diameter but with different impeller diameters. These diameters were 111 mm, 203 mm, 216 mm, 229 mm, and 241.3 mm. The pumps' capacities ranged from 1.5 to 11.2 kW. The pump performance data were extracted from the manufacturer's catalogue and coded into a computer using the MATLAB application designer platform. The virtual laboratory was developed from MATLAB scripts. The scripts were compiled to develop a stand-alone run-time application. The choice to use MATLAB software was based on its robust library for mathematical analyses and graphical plotting. In addition, its components library provides controls that are appropriate for the development of a good interactive user interface. The user's interface form in Figure 3a was designed to capture all essential flow parameters to investigate flow between the reservoir, pipe network, and pump. On the other hand, in Figure 3a, the user's interface with the flow control knob and measurement gauges were used to study the flow provided by the different pumps through the piping system. To perform an experiment that compares the piping system's $NPSH_a$ with the pump's required $NPSH_r$, the flow control knob in Figure 3a user's interface is varied to provide different flow rates. The values of $NPSH_a$ and $NPSH_r$ are read from their respective pressure head gauges. Water at different temperatures, including 25°C, 65°C and 80°C, were used to study the effect of fluid temperature variation on cavitation. Furthermore, the effect of pipeline sizes (diameters) was also considered for the same purpose. The experiments were based on two types of materials: stainless steel and cast iron. The diameters of the two materials were 62 mm, 76.2 mm, and 101.6 mm, respectively.The results obtained from the experiments were plotted for comparison.

The virtual laboratory application has provisions for conducting experiments for different pipe network configurations based on upstream and downstream reservoirs locations. The network parameters for the experiments are shown in Figures 3a and 3b. They were used to investigate cavitation, the effect of pipeline friction, and valve losses on pump performance in the pipe network. The standard parameters used to conduct the experiments were appropriately noted. The virtual laboratory software program generated pumps' power and efficiency contour curves; they were plotted simultaneously with the pipeline characteristic curve. It was possible to study the performances of all the pumps selected for this study using the same pipeline network configurations in Figures 3a and 3b.


Fluid density in Kg/m3: 998
Dyn viscousity: 0.000891
Vapour Pressure N/m2: 3169
Atm Pressure N/m2: 1.013e+05
K elbow loss: 0.3
K roughness in m: 2e-06
@ K E correction fac...: 1
Elev diff in m: 1.2
Pipe diam in m: 0.0762
K for ent. l...: 1
K for ext l...: 1.05
K for flow valve loss: 10
No of Elbow: 3
K for Gate valve loss: 2
Total pipe length in m: 5
Pump: 111mm dia
Flow rate in L/s: 0
Gen NPSH in m: 0
Req NPSH in m: 0

Flow rate in L/s: 0
Pump head in m: 0
Pipeline head m: 0
Brake power in Kw: 0
Pump efficiency %: 0

(a) (b)

Figure 3 (a) User interface for experimental data input and for performing the experiment that compares $NPSH_r$with $NPSH_a$; (b) User interface for obtaining the results of the experiment for matching the pump with appropriate piping systems

3. Results and Discussion

Cavitation avoidance is vital in pumping processes in industries. The effects of water temperature and pump upstream head on cavitation in pumps were investigated, as shown in Figures 4, 5a and 5b. Figure 4 indicates that the temperature of the water plays a significant role in the cavitation process of a pumping system; it also shows pump suction curve which shows the region where cavitation takes place. For instance, the higher the temperature, the greater the chance that cavitation would take place at a low flow rate. The experiments showed that cavitation is less likely to occur in water at 25°C than in water at 65°C and 80°C. From the Figure 4, cavitation begins at a flow rate of 22 L/s in water at a temperature of 80°C, while it commences at 28 L/s in water at a temperature of 65°C. Since the vapor pressure of water increases with temperature, cavitation is more likely to occur earlier at a higher temperature than at a lower temperature. The presence of vapor molecules at the suction line of a pump causes it to pump a mixture of vapor and water. This mixture has a serious erosive effect on the pump casing due to the pressure differential caused by the collapse of bubbles formed by the water and its vapor. The elevation head at the pump upstream section also has significant effects on cavitation occurrence in pumps.

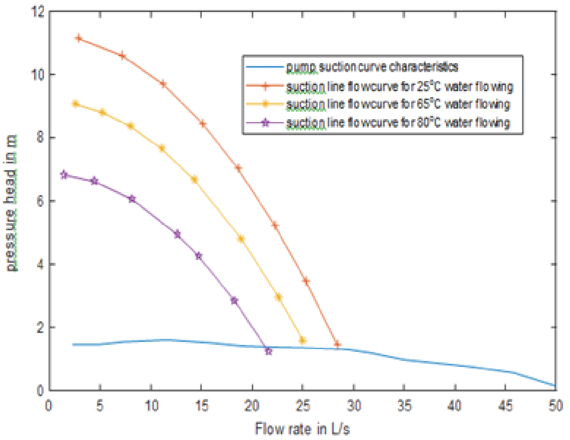
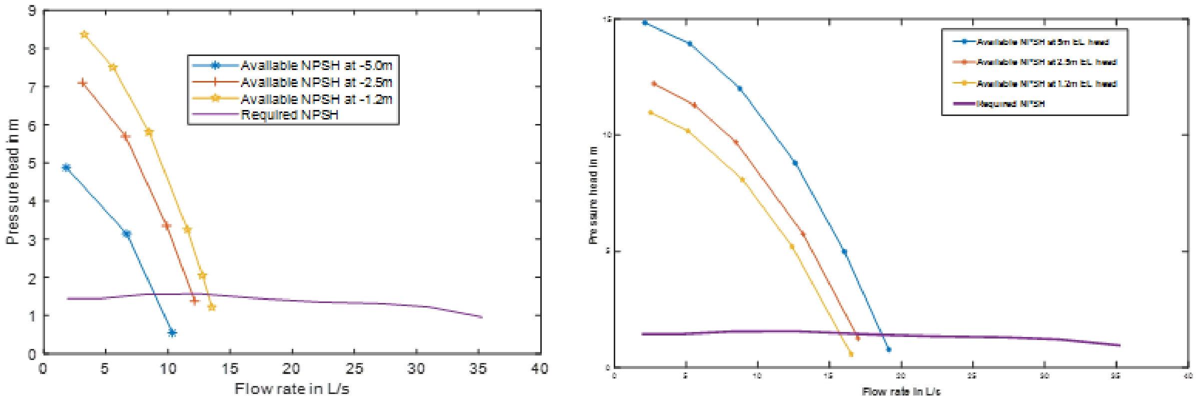


Figure 4 This shows variation of suction line pressure head with the rate of flow given at different temperatures of water

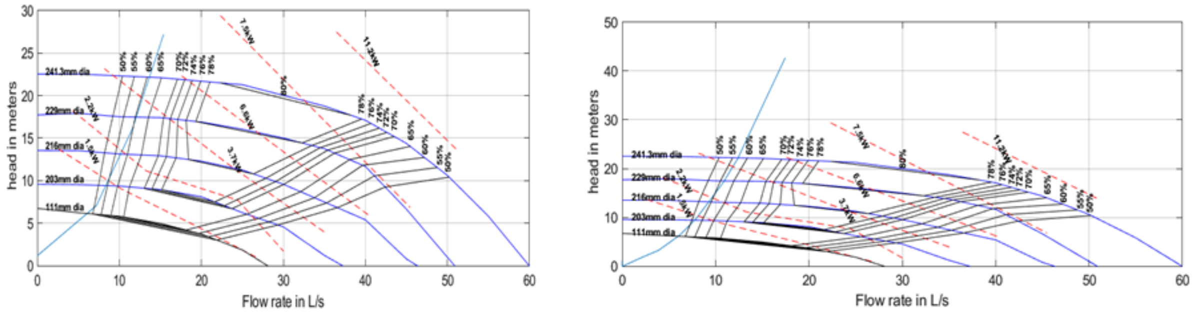
While Figure 5a depicts the variation of pressure head with flow rate for upstream reservoir elevation heads of -1.2 m, -2.5 m, and -5.0 m with respect to the reservoir surface, Figure 5b shows the variation of pressure head with flow rate for positive upstream reservoir elevation heads of 1.2 m, 2.5 m, and 5.0 m with respect to the reservoir surface. The negative experimental curves (Figure 5a) show the available NPSH for each category of elevation heads in the upstream section. Moreover, cavitation first occurs when the elevation head is -5.0 m compared with the other two negative heads. The positive experimental curves (Figure 5b) show the available NPSH for each category of elevation heads in the upstream section. Furthermore, cavitation first occurs when the elevation head is 1.2 m, compared with the other two positive heads.



(a) (b)

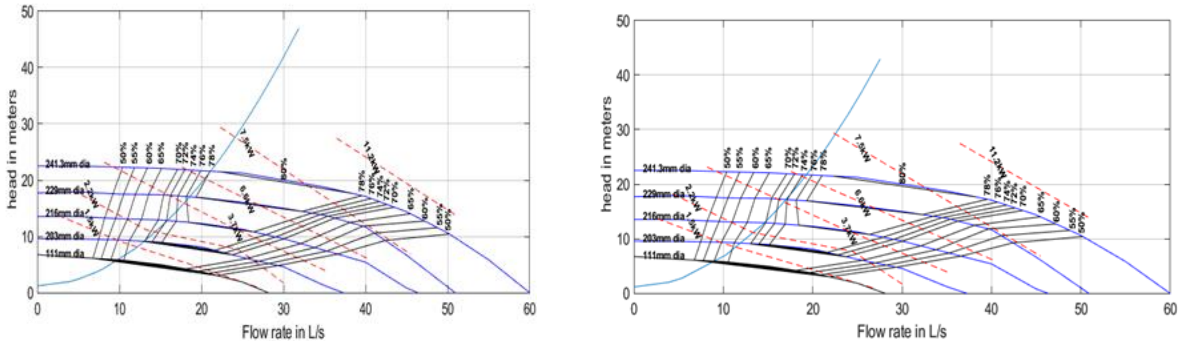
Figure 5 Experimental variation of pump suction line pressure head with flow rate: (a) when upstream reservoir elevation head is negative; and (b) when upstream reservoir elevation head is positive

It can be deduced from Figures 5a and 5b that higher negative pump head at the upstream section of a pump causes cavitation faster than that of the positive pump head. The pumps' characteristics, efficiency contours, and power contour curves are superimposed on the same area in Figures 6, 7, and 8. The system characteristic curves were plotted for 20 m pipeline networks using two different pipe materials, stainless steel and cast iron, with diameters of 62 mm, 76.2 mm, and 101.6 mm respectively. Generally, it can be inferred from all the experiments that friction losses greatly affect the pumps efficiencies. The characteristic curves for stainless steel pipes with diameters of 62 mm, 76.2 mm, and 101.6 mm are depicted in Figures 6a, 7a, and 8a, respectively. From the figures, it is worth noting that the pump efficiencies at the operating points of the different centrifugal pumps were very low when the pipeline diameter was 62 mm. However, the efficiencies improved when the pipe diameters were changed to 76.2 mm and 101.6 mm. This is unsurprising, since a correlation exists between a pipe's efficiency and diameter. In other words, this clearly shows that the diameter of pipes plays a significant role in pipeline flow performance. Furthermore, similar trends were also observed for cast iron pipes with the same set of diameters in Figures 6b, 7b and 8b. However, pumps' efficiencies in stainless steel pipelines under the same conditions show higher efficiency values, indicating better performance.



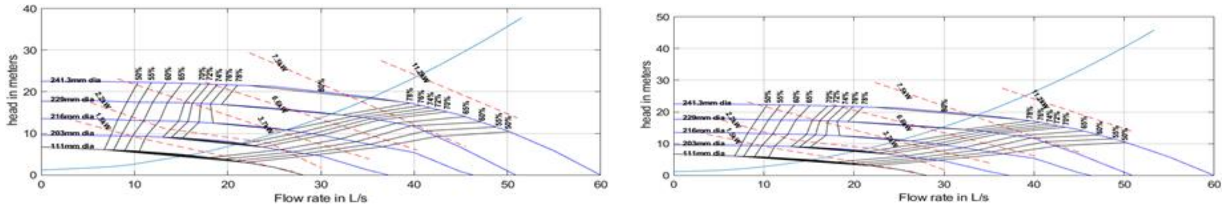
(a) (b)

Figure 6 A 62 mm diameter pipeline head characteristic curve superimposed on pump head characteristic, efficiency, and power contour curves: (a) stainless steel; and (b) cast iron



(a) (b)

Figure 7 A 76.2 mm diameter pipeline head characteristic curve superimposed on pump head characteristic, efficiency, and power contour curves: (a) stainless steel; and (b) cast iron



(a) (b)

Figure 8 A 101.6 mm diameter pipeline head characteristic curve superimposed on pump head characteristic, efficiency, and power contour curves: (a) stainless steel; and (b) cast iron

This is likely because the roughness factor of cast iron is higher than that of stainless steel. It should be noted that, in pipeline design, pipe diameters cannot be arbitrarily increased for economic reasons. In this respect, the optimization process must be carried out on pipeline diameter, flow rate, power consumption, and pipeline materials to achieve optimum system efficiency and minimize costs.

4. Conclusions

The development of a virtual laboratory was carried out to examine the effects of water temperature and elevation head on cavitation, as well as how the pipe diameter and pipe roughness factor affects pump performance in a pipeline network. Simulations were carried out for impeller diameters of 111 mm, 203 mm, 216 mm, 229 mm, and 241.3 mm with pump power ranging from 1.5 to 11.2 kW. Water flow in pipes was investigated with materials made up of stainless steel and cast iron of diameters 62 mm, 76.2 mm, and 101.6 mm at temperatures of25°C, 65°C, and80°C, respectively. The results showed that at a temperature of 20°C, cavitation commenced at a flow rate of 29 L/s, while at a temperature of 80°C, cavitation started at a flow rate of 22 L/s. Similarly, when the pump upstream elevation was -5 m (5 m below the pump inlet port center), cavitation commenced at 13 L/s. When the pump upstream elevation was placed at +5 m (5 m above the pump inlet port center), it flowed at 18 L/s. It was inferred that a negative potential head and high fluid temperature increased early cavitation incidence, while a low fluid temperature and positive potential head reduced it. Furthermore, it was revealed that the choice of pipe diameter and the roughness factor of the pipe material played significant roles in pump performance. A virtual laboratory could be a useful tool for training and educating individuals on pipeline and pump flow matching to increase efficiency optimization under any circumstance that makes physical laboratory utilization difficult.

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