A study case of cavitation venturi flow control feature in a centrifugal pump liquid viscosity replacement

Sarkaut Ahmed Ameen
Automotive Technique Department, Erbil Technology College, Erbil Polytechnic University, Iraq
Pshtiwan Mohammad Sharif
Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
Haider Omar Rashid
Ministry of oil-Kirkuk Oil Training Institute, Iraq

Corresponding author: Sarkaut Ahmed Ameen

Abstract: Preventing the occurrence of cavitation erosion phenomenon in centrifugal pumps poses a major challenge for this type of equipment due to the creation of saturated vapor pressure at the impeller suction. This paper describes an experimental investigation of cavitation phenomena in a semi-open single-suction centrifugal pump liquid replacement influence in heavy viscosity oil system, a selective study pump validated through numerical and experimental study. The success of the process introduced a successful financial reduction cost and life operation influence to the system due to pump replacement. The study was carried out to investigate two various viscosity liquids by observing the formation of vapor bubbles at high flow velocity visualizing inspection by observing through the transparency Venturi test bench. The venturi tube was used under controlled flow conditions characterized by discharge coefficient function, and the experiment was carried out under standard venture geometry from the previous study. The cavitation prediction was based on the fluid viscosity change method, which was found to be more suitable for the newly replaced liquid. The results showed a significant influence in pressure head development and vapor bubble formation occurs at a higher pump speed of (2000RPM) compared to the previous (1850 RPM) with lower noise within (9% -10%) beneficial for the new liquid use.

Keywords: cavitation; centrifugal pump; venturi; Numerical simulation; vapor pressure

INTRODUCTION

Cavitation in centrifugal pumps is a common physical phenomenon defined through the formation of the vapor phase in liquids when subjected to conditions of low pressures [1,2]. While the centrifugal pump is running, the pumped liquid pressure around the impeller areas will lead to suction line pressure being lower than the saturated vapor pressure, resulting in body cavitation [3,4]. The repeated excitation impact of vapor bubbles leads to cavitation in the area of the blade surface which may cause damage [5]. At the same while, the noise increased with severe vibration in the centrifugal pump [6]. The cavity area increases rapidly if the suction pressure continues to decrease to a certain range inside the pump [7], leading to fatal failure in the pump body and its performance [8].

Thus, ensuring a reliably safe pump operation under the cavitation state is required to understand cavitation incipiently and how cavitation developed within pumps, same as analyzing the influence of liquid viscosity effects on the pump cavitation [9]. The best practical way to regulate the flow rate is by using a venturi cavitating test rig where the cavitating venturi is a kind of obstruction flowmeter observatory that takes advantage of the Bernoulli theory principle of liquid flow controlling to the desired rate [10][11].

The present work details the testing of the liquid cavitation venturi that is used to regulate the propellant liquid suitable for the selected centrifugal pump. Tests were conducted to determine the venturi discharge coefficient.

Zhenfa et al. [12] have conducted visualization applied experiments at different blade speeds studying the influence of vapor bubbles on impeller surface temperature and cavitation occurs at a high-speed range. The results show a significant cavitation performance under extremely low flow rates was

The International Journal of Learner Diversity and Identities
Volume 31, Issue 1, 2024, http://ijldi-cgrn.com/

ISSN: 2327-0128 (Print), ISSN: 2327-2627 (Online)

worse than under design conditions. Zhiyi Yuan et al. [13] show the influence of pressure graduation as cavitation takes place when the pressure variation leads to mass transfer and temperature gradient which cause the boiling process of liquid to be heated at low pressure until its saturation pressure reaches its local pressure level which leads to the pressure gradient. Di Zhu [14] in his study of cavitation flow in pump turbines has shown quite a complication compared to the fundamental structures due to the rotation of high-speed rotary blades. The observation of cavitation takes place at the pump suction side of pump blades under the low flow rate while the high-pressure side is under at discharge. The exitance of obstacles in the flued presented significant development cavitation on the surfaces of blades of the centrifugal pump as showed by W Zhao et al. [15] this study presented the influence of liquid purified and filter use to prevent cavitation. The pumped liquid leads to mass transfer pressure drops gradually at the section line which causes local pressure drops till reaching saturation temperature then cavitation takes place [10]

There was an attempt to replace the pumped system circulated liquid used by the centrifugal pump single stage with a new viscous liquid (0.25 CS) instead of (5.0377 CS) in the system. The previous liquid was causing cavitation in the pump blades and noises. That is why the study helps to ensure the qualification of the liquid for the system and the prevention of cavitation to the pumps as much as possible.

The converging-diverging geometries method for the circular cross-section is generally used in experimental flow rate measurements [16] in both cases of (no cavitation occurring) and (pressure difference of both sides of venturi (ΔP)). The selected Venturi tube geometry that was proposed for liquids flow visualization is the type (Nozzle-Venturi) that is shown in Figure 1, where the ΔP measurement parameter was used to find the flowed flowing mass rate $(\dot{m})$ in the test bench pipe as indicated by [17].

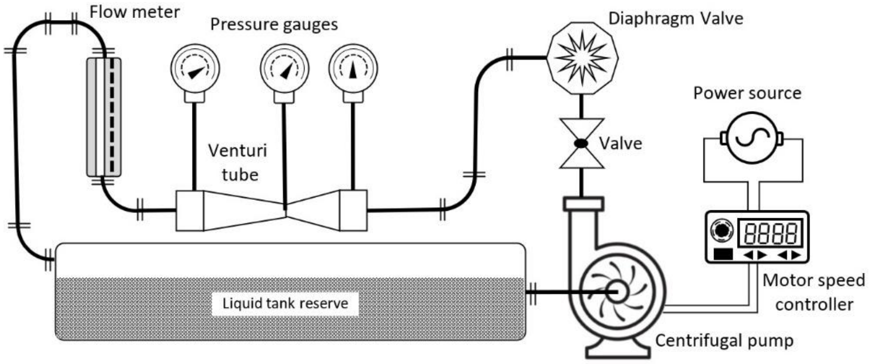

Figure 1. Schematic of the experimental setup

While cavitation conditions have occurred, Venturi tubes will visualize the vapor bubbles created in high-speed flow and pressure to be compared [18].

The cavitation phenomenon in the liquid flow can be characterized within the ratio of the outlet's flow pressure to the flow saturation pressure proportional to the pressure dynamic measured at the Venturi throat's cross-section, the dimensionless numbers of cavitation number (σ), cavitation index (σ_v) are used to assess the proneness to cavitation

$$\sigma = {(P_{in} - P_{vap})}\Big/{0.5\,\rho V_{in}^{2}} \tag{1}$$

$$\sigma_v = {(P_u - P_{vap})}\Big/{(P_u - P_d)} \tag{2}$$

Where P_{vap} is the saturated vapor pressure and (P_{in}, V_{in}) are pressure and velocity at the reference location measured. P_u and P_d are the pressures upstream and downstream of the valve.

The other parameters are losses in pressure due to the component's hydraulic resistance of elbows, valves, or orifice surface plates expressed by pressure loss coefficient

$$\xi = {(P_{in} - P_{out})}\Big/{0.5\,\rho V_{in}^{2}} \tag{3}$$

The converging-diverging geometries used as flow metering devices to visualize the vapor bubble of cavitation conditions have been used to study Venturi's geometry performance within various operational status visualizing comprising regimes of cavitating and non-cavitating conditions [19,20]

Furthermore, the energy transformation theory of a pump impeller is functional in its angular momentum energy and the number of impeller blades.

The use of CFD platform simulation was used to compare both centrifugal pump impellers pumping flow status in case of a change of liquid viscosity for six-blade impeller. From the output results of the simulations, a preunderstanding of the suitability of the new fluid could be visualized.

This paper presents an experimental investigation conducted on a closed-loop flow circuit determining the effects of liquid viscosity on cavitation influence depending on vapor bubble occur condition using the Venturi as a visualizer in two methods, the first test at the constant flowing condition of the liquid flow with a variation of pump speed then observes cavitation regimes condition vapor bubbles within the transparency Venturi. The second experiment was conducted within constant pump speed and change of liquid flow rate. The obtained results details demonstrate a dependency relationship between both flow rate and pumped inlet pressure by the pump speed within the cavitating regimes. As a result, the selected replaced liquid proposed validated and overcomes the accepted condition to be found suitable for cavitation reduction for the same pump. The viscosity influence on the pump performance within the impeller was investigated based on the experimental process.

NUMERICAL APPROACH

The Numerical process was conducted to study the theoretical influence of liquid velocity replacement on the test pump impeller specified in Figure 2 using the simulation platform CFD.

2.1 Studied pump

A centrifugal pump single-stage semi-open impeller is used in the present study (Figure 2) to investigate the influence of changing the liquid viscosity. The pump impeller's main specifications are given in Table 1.

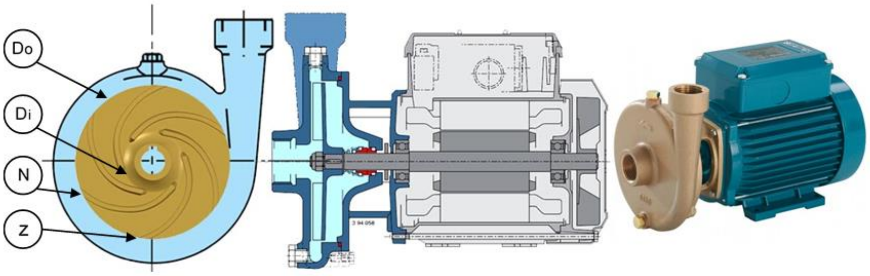

Figure 2. Tested pump type and impeller specified [21]

The centrifugal pump with a semi-open impeller is designed based on the manufacture design scale.

Table 1. Centrifugal pump manufacture design specification

Outlet diameter - Do	150 mm	outlet width	10 mm
Inlet diameter - Di	58 mm	number of blades - N	6
Outlet blade angle - βo	26°	Blades' thickness - t	4 mm
inlet width	21 mm	Impeller material	copper

2.2 Computational model

Numerical calculations FLUENT software performed in turbulence model and computational impeller area domain was as a rotational domain while rest area domains were set to static. the pressure was set in atmospheric status reference. The boundary condition is applied as a standard wall surface function and calculation method.

For three-dimensional incompressible, flowing unsteady, the equations of continuity and momentum can be expressed as follows:

$$\left({}^{\partial_\rho}\!\big/_{\partial_t} \right) + \nabla.(\rho U) = 0 \tag{4}$$

$$\left({}^{\partial_\rho\, U}\!\big/_{\partial_t} \right) + \nabla.(\rho U * U) = \nabla.\left(-p\delta + \mu_{eff}(\nabla U + (\nabla U)^T)\right) + S_M \tag{5}$$

U is the velocity; p is the pressure; ρ is the density; S_M is the source term and μ is the effective viscosity coefficient, δ is the identity matrix.

Governing Equations for ANSYS platform numerical simulation are carried out to solve mathematical modeling. Since the used liquid pumped is incompressible and the flowing status is steady state,

$$\nabla.\bar{u} = 0 \tag{6}$$

The equation of conservation of momentum together with the definition of the source term is expressed as

$$\partial\!\big/_{\partial_t} u_i + \partial\!\big/_{\partial x_i} u_i = {}^{-1\,\partial}\!\big/_{\rho\, \partial x_i} p + v\, {}^{\partial^2}\!\big/_{\partial x_j\, \partial x_j} u_i + S_M \tag{7}$$

The source term S_M (including the centrifugal and Coriolis force terms) is written as in Eq. (8) and the Reynolds-stress tensor obtained from Eq. (9):

$$S_M = -\rho[2\omega \times u + \omega \times (\omega \times r) \tag{8}$$

$$\tau^R = -\rho\, \bar{u}\bar{u} \tag{9}$$

The Computational Domain of the design consists of four zones: inlet, side gab, impeller, and volute with outlet.

EXPERIMENTAL FACILITY

3.1 Test rig

The experimental setup test rig adopted in this experiment is illustrated in Figure 1. The piping system is a closed-loop cycle that is powered by a 1.2 kW type C 16/1E centrifugal pump. Liquid tank reservoir, a transparency Venturi tube, pressure gauges, and flow rate meter.

The system boundary condition concerns the atmospheric pressure, while the cycle flow rate is controlled by the electric rotating speed motor pump, the liquid flowing ratio is controlled by the Diaphragm Valve. The pump's electric motor rotation speed was controlled through a variable frequency drive (VFD). The obtained pump maximum speed in this test was 2700 RPM and the system's reference pressure is considered as free surface pressure. The obtained absolute pressure range reached on both sides of the venturi tube was (-0.77 bar to 1.5 bar). The liquid temperature operation is 16.7 Cº. The data reading from sensors was obtained while testing with vapor occurs visualizing observation was conducted.

3.2 visual Cavitation regimes

A transparency Venturi nozzle type made from Poly (methyl methacrylate) which can visualization the vapor bubble cavitation phenomena of a total length of 230mm with circular cross-sections inlet and outlet section of 25mm diameter and 4.5mm throttle cross-section designed and used for the present study. flowing through a converged nozzle causes an increase in liquid velocity and a subsequent drop in its pressure. A pressure drop of liquid below its saturation point temperature will cause the forming of a vapors bubble at the throttle zone limiting the amount of liquid flowing, thus effectively limiting the flow rate flow to the desired rate [22]. The pressure sensors are located at the throat section and inlet section. parent. During the test, the vacuumed pressure occurred due to the high speed of the impeller, which influenced the liquid boiling point to be less than its saturated temperature leading to the creation of vaporized liquid.

3.3 Working liquid

In the experimental process, each working liquid was tested at a boundary condition of 16.7C°. The density and the kinematic viscosity of the original liquid used are 5.0377CS and the replacement liquid is 0.25CS respectively. The comparison of the study will validate the use of the replacement liquid that needs to be used in the system.

EXPERIMENTAL PROCEDURE

4.1 Calibration and uncertainty of Measurement instruments

Device and instrument calibration is the essential process that should be conducted before any use for measurements to ensure less error and uncertainties in the data gained [23]. The measurement instrument hardware was calibrated in the university test laboratory and uncertainty was calculated in the average of standard deviations. The calibrate devices are the pressure gauge ±2 kPa, temperature sensor ±0.1C°, and liquid flowmeter was lower than 1% error.

4.2 Liquid degassing process

The experiment was conducted on liquid pumping and liquid visualizing of vapor bubbles of cavitation phenomena that occur inside the liquid. The presence of formed dissolved gasses and particles presence inside the liquid influenced the behavior formation of cavitation and visualization [24], which is why filtration and degassing of the system are required which is done by applying the vacuum process on the liquid reserve tank [25], the solubility gasses inside the liquid will reach the vapor pressure point. As a result, the liquid boiling temperature under vacuum becomes oversaturated and begins to decrease. Furthermore, the filtering will ensure a clean liquid status. Later, the reserve tank will be re-pressurized to atmospheric pressure and require test temperature.

4.3 Tests process outlet

The testing selected process operation was nominated based on the centrifugal pump facility and operation, which was used as fluid pressure and volumetric flow rate reference required to operate at a controlled temperature of 16.7C°. Adopted test conducted for two liquids in two terms for each liquid; constant flow rate with various in the pump speed range of (1000 to 2700 RPM). The second test was conducted at a constant speed of (1850, 2000 RPM) and the suction line flow reduction was controlled at (800 – 350 L/hr) for the original liquid and (825 – 325 L/hr) for the replaced liquid. The liquid flow was controlled through the control valve opening ratios from fully open to minimum flow. In other research, the following can be mentioned:Taghipour et al.[26] studied The impact of ICT on knowledge sharing obstacles in knowledge management process (including case-study). Mohammadi et al.[27] studied “Investigating the role and impact of using ICT tools on evaluating the performance of service organizations. Taghipour.[28] studied A review of the sustainability indicators’ application in vehicle routing problem. ” Moosavi and Taghipour.[29] studied Turbine vibration condition monitoring in region 3. Taghipour and Vaezi.[30] studied Safe power outlet. Taghipour et al.[31] studied “ Assessment of the Relationship Between Knowledge Management Implementation and Managers Skills (Case Study: Reezmoj System Company in Iran)”. Taghipour et al.[32] studied “Evaluation of the effective variables of the value engineering in services. Hosein pour et al.[33] studied “The problem solving of bi-objective hybrid production with the possibility of production outsourcing through Imperialist Algorithm, NSGA-II, GAPSO Hybid Algorithms.” Taghipour et al.[34] studied Project Planning and Control System in Multi-project Organizations under Fuzzy Data Approach Considering Resource Constraints(Case Study: Wind Tunnel Construction Project). Molavi and Taghipour.[35] studied A survey on electrical cars advantages. Taghipour and Yazdi[36] studied Seismic analysis (non-linear static analysis (pushover) and nonlinear dynamic) on Cable-Stayed Bridge. Taghipour et al.[37], studied Application of Cloud Computing in System Management in Order to Control the Process. Taghipour et al. [38] studied “Identification and modeling of radio wave propagation channel in industrial environments. Taghipour et al. [39] studied Implementation of software-efficient DES Algorithm. Sedaghat manesh & Taghipour.[40] studied Reduction of losses and capacity release of distribution system by distributed production systems of combined heat and power by graph methods. Taghipour et al.[41] studied A survey of BPL technology and feasibility of its application in Iran (Gilan Province).

RESULTS

The results demonstrate the liquid comparison characteristic between the original liquid and replacement liquid to validate the qualification and suitability of the new liquid for use with the centrifugal pumps in the system.

5.1 Theoretical results

The centrifugal pump performance is illustrated in two comparison results, the pump pressure involved inside the impeller casing in case of viscosity change.

Based on the CFD solution figure, the replaced liquid illustrated the better performance of static pressure distribution inside the 6 impeller casing flow and reduction in cavitation prediction by replaced liquid shown in Figure 3.

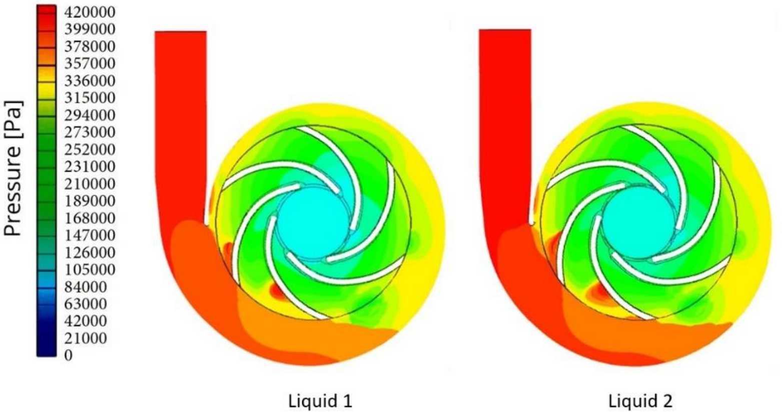

Figure 3. Pressure contour for different flow rates for compared liquids

From the simulation results, it can be identified that the model with lower liquid viscosity has been shown a better higher impeller head within, and the occurrence of vapor cavitation can be presented in the higher viscosity liquid. The property of the high kinetic viscosity density of the original liquid caused the forming of vacuum gaps while pumping leading to the introduction of vapor cavitation, especially at a high impeller rotation speed.

Therefore there was a huge noise and cracking while the experimental test conducted a 2000RPM opposite to the replacement liquid which has a very lower kinetic viscosity compared to and did not show any cavitation vapor at the same rotation speed.

5.2 Experimental results

The experimental process was implemented with two processes in case of various pump pressures and various pump flowing. The vapor volume fraction was used for the cavitation evolution demonstration. To characterize the formation of the cavitation vapor in the Venturi tube based on the Venturi's inlet cross-section hydraulic diameter and liquid flow pressure with consideration to the liquid density influence and liquid dynamic viscosity, the experimental results of the pressure variation demonstrated a convergence in results till reaching the speed limit where the vapor bubbles occurred and diversion in results formed as shown in Figure 4.

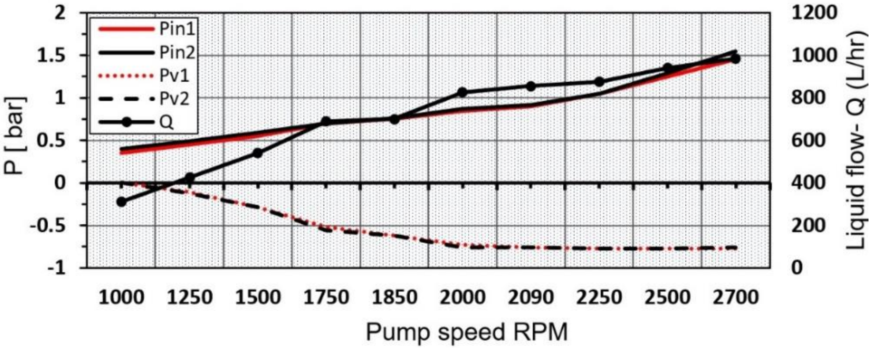

Figure 4. Venturi flow meter comparison reading at varying pressure ratios for both liquids

Figure 4 illustrates the pressure ratio at various pump speeds of liquid input venturi pressure (Pin) and the throttle line vaporized pressure (Pv) for the original liquid and replacement liquid. The reduction in pressure flow created at vacuum status with the increase in flow speed due to viscosity density influence as liquid consistency is high that is why the original liquid with higher kinetic viscosity introduced vapor cavitation at an earlier stage compared to replacement liquid.

In the experimental case of a constant flow rate at fully open throttle, the variation was in impeller speed. The comparison presented a divergence at the high impeller speed and forming of vapor cavitation at a speed of 1850 RPM for the original liquid and the second liquid started at a speed of 2000 RPM as shown in Figure 5. Replacement liquid showed a benefit of 4.63% resistance to cavitation compared to the original liquid which the cavitation regime started in 2000RPM.

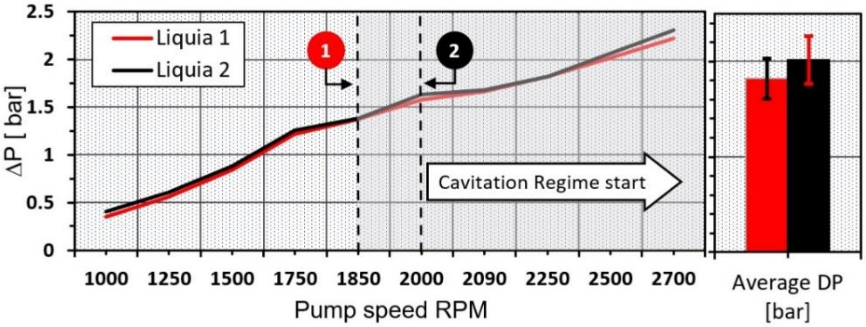

Figure 5. The cavitation regime occurs indicated by the pump rotation speed

In the case of a constant impeller rotation speed at 1850 and 2000 RPM with the variation in liquid flow reduction. The comparison presented the cavitation regime to stop at 700 L/h flow rate for the original liquid and the second liquid started to stop the cavitation regime at a flow rate of 725 Figure 6. The replacement liquid showed better resistance to cavitation compared to the original liquid.

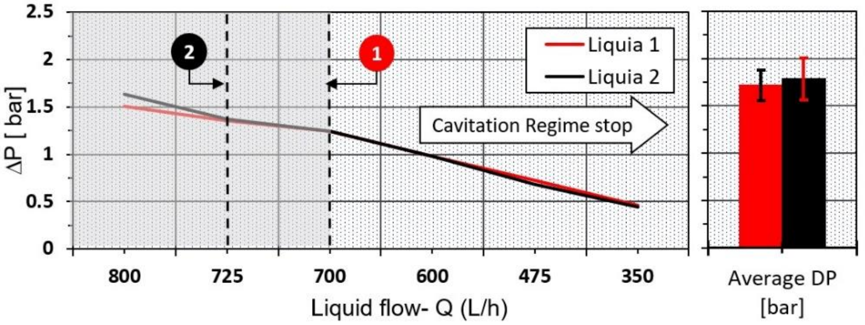

Figure 6. Cavitation regime influenced by liquid flow rate

The Venture transparency helped to visualize the vapor bubbles formation clearly within the experimental process, selected Venturi's inlet was considered as measured pressure reference to be a function for the volumetric flow rate measuring Figure 7. With the development of cavitation inside the Venturi, the measurement process was collapsed to be dependent on flowing pressure.

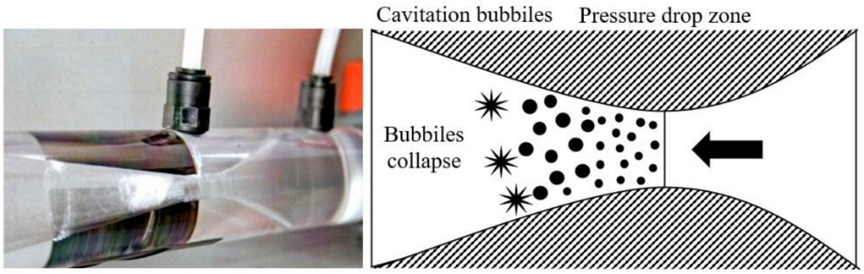

Figure 7. Experimental cavitation formation passes liquid through a Venturi tube

The pump head pressure for both liquids showed a better average performance of 6% higher pressure by the replacement liquid leading to a higher volume flow rate in a safe range of impeller sped with prevention of cavitation formation within the operation pump speed Figure 8.

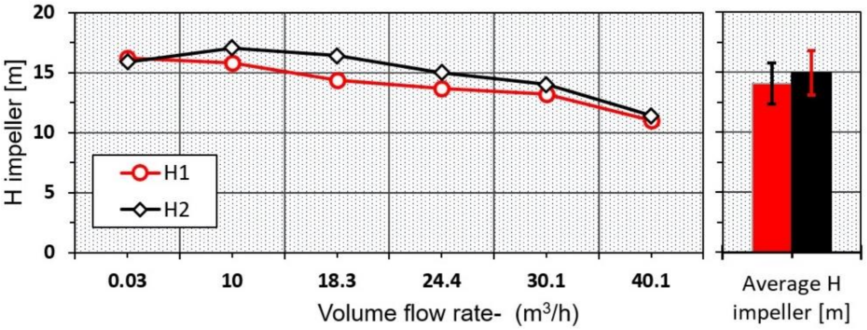

Figure 8. Impeller head performance comparison

CONCLUSIONS

In conclusion, the utilized transparency cavitating venturi design was validated experimentally for flow rate control for both used liquids in steady-state operation in the condition of impeller rotation speed. Moreover, the dependent pressure ratio is implemented to predict the vapor cavitation throughout the entire pressure ratio range. Test results and observation identified that the replaced liquid has been shown to better perform influence in pump power consumption reduction, cavitation erosion prediction, and higher volume flow rate increases. As a result, the new liquid replacement introduced the best suitability in use with the selected pump system that will be installed in the system with cost and operation reduction due to pump electric power consumption reduction and purchasing cost compared to the original commercial pump.

Acknowledgments

The authors declare that they have no conflict of interest.

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