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Engine Room Simulators
Симулатори на машинното отделение

EDUCATION PROCESS FOR STUDENTS AND MARINE ENGINEERS OF AN EXPERIMENTAL UNIT FOR CAVITATION FLOW IN WATER-PIPING SYSTEM

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Abstract. The main objective of this report is to give basic instruction to trainees about the operation and capabilities of an experimental unit for cavitation research. The equipment is designed and fabricated for the needs of students from the Faculty of Engineering. Cavitation is a complex process that can be observed at various locations in piping systems, both in the suction and discharge lines. Uncontrolled cavitation in pumps, valves, pipes cause failure. By knowing and managing the process, cavitation can be controlled and transformed from undesirable to desirable with a positive outcome.

Keywords: education; cavitation flow; experimental unit; centrifugal pump; performance

Introduction

For the needs of the educational institution and the training of the students of the Faculty of Engineering, we developed an experimental unit to study the causes of cavitation in different locations of the system, as well as to study the change in the resistance of the system. The fabricated water-piping system (Figure 1) is equipped with a Venturi tube, pressure sensors, pressure gauges and control module. The stand is designed to allow future upgrade and improvement of control and measurement modules, process visualization. The variable frequency drive (VFD) of the three-phase electric motor plays a key role in the study of the characteristics of the centrifugal pumps. Flow throttling and changing the system resistance are also possible options to explore.

1. Description of the experimental unit

The stand is a water pipe transferring system. Hydraulic energy is transmitted to the fluid by a centrifugal pump driven by a three-phase electric motor with VFD control. The stand is multifunctional, easily applicable to different types of research devices, measuring instruments, pressure sensors, transmitters, etc.

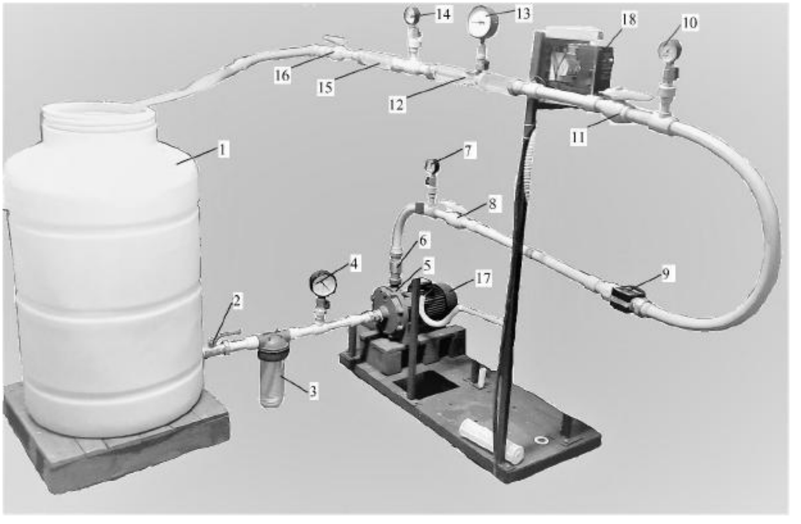

Figure 1. Pictorial diagram of the Experimental unit

The fabricated experimental unit (Figure 1 and Figure 2) consists of:
1 – water reservoir;
2, 8, 11, 16 – throttling valve;
3 – filter;
4, 7, 10, 13, 14 – pressure gauge;
5 – centrifugal pump;
6 – non-return valve;
9 – digital flow meter;
12 – transparent Venturi pipe (replaceable part);

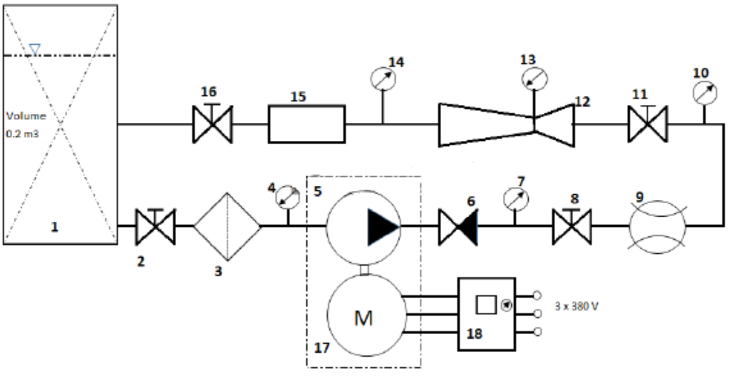

Figure 2. Schematic diagram of the experimental unit

15 – transparent sight pipe (replaceable part);
17 – 3-phases electrical motor;
18 – VFD module.

2. Description of the schematic circuit diagram (Figure2)

The centrifugal pump (5) starts a suction process from water reservoir (1), through valve (2) and filter (3) reaching the eye of the impeller. The centrifugal pump's impeller converts mechanical energy into hydraulic energy using centrifugal force acting on the fluid. The pump flow rate is displayed on the flow meter (9). A water flow with increased pressure enters the Venturi tube (12). The pressure (13) drops down in the nozzle end up to vapor pressure of the water. The Venturi pipe is made of transparent material and the formation of cavitation is observed. The tube (12) is a replaceable element and can be replaced with another device with suitable length and fittings. The changes in the laminar flow and the formation of bubbles are observed through the transparent tube (15). The beginning of cavitation is controlled by throttling valve (11) in the discharge part or by a valve (2) in the suction part to start the cavitation process in a vacuum environment in the filter (3). Cavitation in the Venturi tube can also be controlled by changing the speed of the centrifugal pump through the VFD (18).

3. Main components and they characteristics

3.1. Centrifugal pump

In the outlet connection of the centrifugal pump, the resulting increase in speed is converted into delivery head H (m). In centrifugal pumps, the delivery head H depends on the flow rate Q (m^3/h). This relationship, also called pump performance, for used pump Conforto model, STD-3 type[1] is illustrated by H/Q curve (Figure 3).

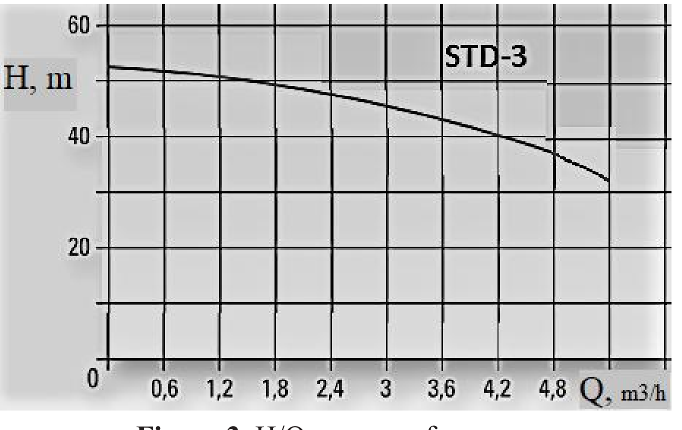

Figure 3. H/Q pump performance

During a bench test, the values Q and H are determined for the various operating points. Depending on the required delivery head, the centrifugal pump will find its operating point when the system curve Hs and pump curve Hp meet (Figure 4). The required operating point is obtained by adapting the pump to the specified operating conditions by the following actions:

– Throttling the water flow

– Adjusting the speed of the electrical motor by VFD

Partially closing a throttle valve 11 or mounting an orifice plate in place of Venturi pipe will increase the pressure drop. The system curve Hs is shifted to Hs1 (Figure 4).

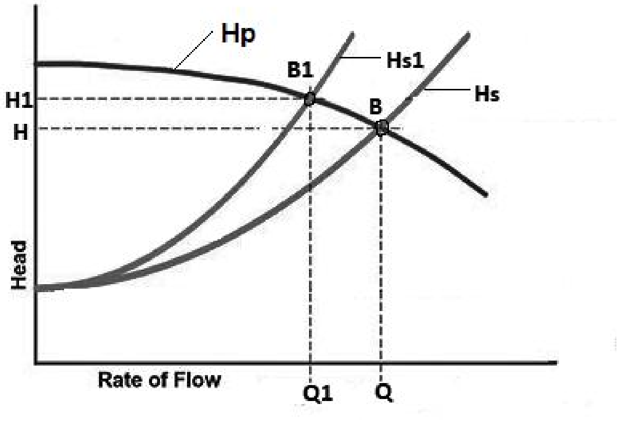

Figure 4. Operating points

The operating point B moves on the pump curve to point B1. The throttling reduces the overall efficiency of the pump.

The Venturi tube is a replaceable pipe and, in its place, a pipe with orifice can be mounted (Andrew 2011) (Figure 5). The friction loss (Antonov, Velichkova, Terziev 2010) in an orifice plate is calculated easily by equation (1):

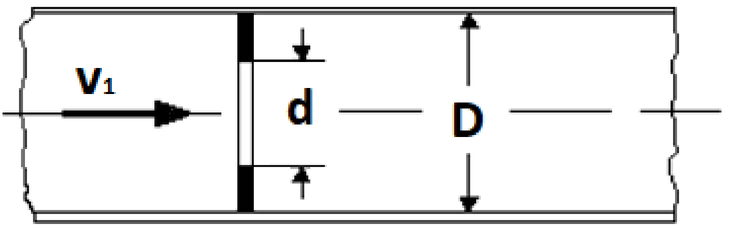

Figure 5. Orifice flow resistance

$$\Delta p_v = \zeta \frac{(\rho v_1^2)}{2} 10^{-5} \qquad (\,SEQ\ Equation\ \backslash{*}\ \ ARABIC\ 1)$$

Where,
ρ, [kg/m³] – water density
v_1, [m/s] – flow speed
ζ – orifice resistance
Δp_v, [bar] – pressure drop.

The values of the orifice resistance ζ has following relation with diameters D and d (Figure 6):

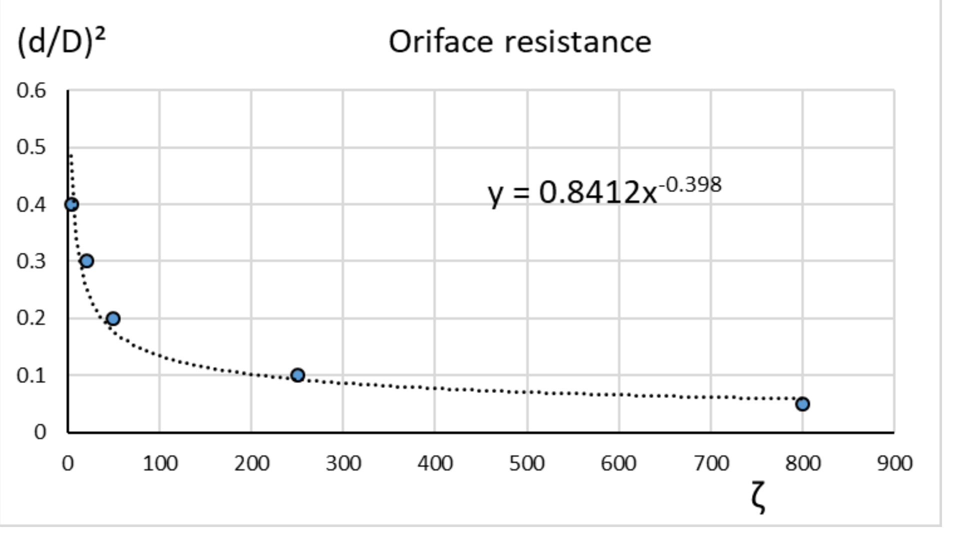

Figure 6. Orifice resistance

3.2. VFD module with 3-phases electrical motor

The used VFD model Elmark is ELM2000-0015 T3 type. The Drives ELM2000 type are the newest generation of inverters, designed to general purpose, for a wide range of applications, from the simplest speed control to the most complex process automation system. High-tech motor control concept is based on advanced DSP-technology, sensorless[2]. Ready for all commonly used fieldbus systems. A great number of various operating points can be set continuously, when modifying the pump speed using a VFD or frequency inverter. The operating point moves on the pump curve from B to B1, B2, B3 (Figure 7). Considering the overall efficiency, this is the best way of flow control (Ciuc, Georgescu, Dunca, Bucur 2019).

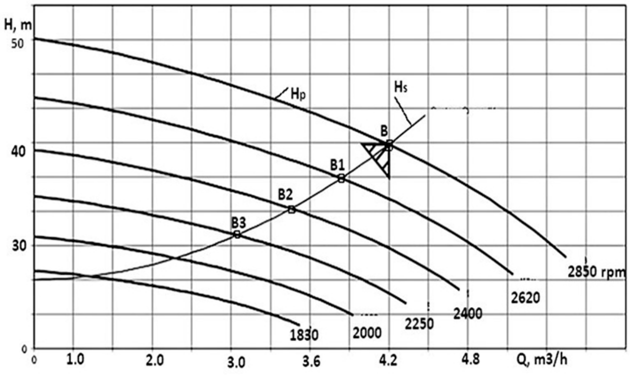

Figure 7. Pump performance curves by VFD

3.3. Digital flow meter

The pump rate is measured by digital flow meter model PIUSI K24-A with turbine impeller. The K24-A flow meter guarantees a metering accuracy of +/- 1%. The minimum measured flow rate is 7 l/min. The maximum measured flow rate is up to 120 l/min. Maximum operation pressure is 20 bar. By using the below equation (2) and (3), the flowrate velocity v for steady uniform flow can be determined as follows:

$$Q = A.v,\ [m^3/s] \quad (2)$$

$$v = \frac{Q}{A},\ [\frac{m}{s}] \quad (3)$$

Where,

A – cross-section area,

v – flow speed

Q – measured flowrate

3.4. Venturi pipe

The experimental unit is equipped with a Venturi tube (Figure 8) by measuring instruments to investigate Bernulli's principle. The pipe is made of transparent polypropylene material.

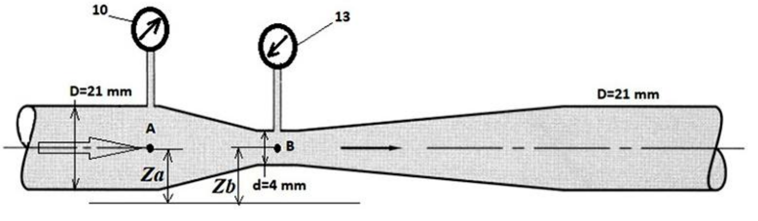

Figure 8. Venturi tube with measuring points

According to the Bernulli's principle (Hibbeler 2014) it is in force (4):

$$p_a + \rho \frac{v_a^2}{2} + \rho g z_a = p_b + \rho \frac{v_b^2}{2} + \rho g z_b \qquad (4)$$

$$z_a = z_b \qquad (5)$$

$$\frac{p_a}{\rho * g} + \frac{v_a^2}{2g} = \frac{p_b}{\rho * g} + \frac{v_b^2}{2g} = const. \qquad (6)$$

But the flowrates Q at point A and point B are equal, so it is in force (7) and (8):

$$v_a \frac{\pi D^2}{4} = v_b \frac{\pi d^2}{4} \qquad (7)$$

$$v_a = v_b (d/D)^2 \qquad (8)$$

Flow speed at point B is determined by the equation (9):

$$v_b = \sqrt{\frac{2(p_a - p_b)}{\rho[1 - (\frac{d}{D})^4}} \qquad (9)$$

Where,
p_a – Pressure at cross-section A
h_a – Height of water column at cross-section A
v_a – Flow velocity at cross-section A
p_b – Pressure at cross-section B
h_b – Height of water column at cross-section B
v_b – Flow velocity at cross-section B
ρ – Density of water
3.5. Filter element

A pump creates a suction head to pull liquid from the reservoir. The suction head is the vertical distance from the pump's centerline to the surface of the liquid in the reservoir. If the suction head is too large, the pump creates a vacuum effect, allowing vacuum cavitation. Other causes of vacuum conditions in a suction line are a dirty filter or clogged inlet line. In each case, not enough liquid enters the pump, allowing more vapor bubbles to enter the impeller. The first step to avoiding cavitation in pumps is proper system design. This means ensuring that the inlet's Net Positive Suction Head (NPSH) is high enough. The NPSH measures how much higher the absolute pressure is than the flowing liquid's vapor pressure. Combining the three components, pressure head, atmospheric head, and velocity head, results in absolute pressure (10):

$$\frac{p}{\rho g} + \frac{p_a}{\rho g} + \frac{v^2}{2g} - \frac{p_v}{\rho g} > 0 \qquad (10)$$

Where,
p – pressure
p_a – atmospheric pressure
v – liquid velocity
ρ – liquid density
Pv – vapor pressure
g – gravitational acceleration

3.6. Pipeline

The pipeline is made of Polypropylene Random Copolymer known as PPR pipe with minimum pressure loss. Pressure loss in a pipe is convenient to understand and calculate using the Hazen-Williams Equation (11) (Yunus, Jonh 2018):

$$h_{fr} = \frac{kLQ^{1.85}}{C^{1.85}d^{4.87}} \tag{11}$$

Where:
h_{fr} – head loss due to friction
k – constant based on unit system (0.85 for metric, 1.32 for imperial)
Q – Volumetric flow rate
L – Length
C – Pipe roughness coefficient (1 = smooth, <1 = rough)
d – Pipe diameter

And Minor Loss is calculated as follows (12):

$$h_m = K\frac{v^2}{2g} \tag{12}$$

Where:
h_m – minor head loss
k – minor loss coefficient
v – flow velocity
g – acceleration due to gravity
And finally, the Total Head Loss (System head loss) h_{loss} is equal to (13):

$$h_{loss} = \frac{kLQ^{1.85}}{C^{1.85}d^{4.87}} + \Sigma K\frac{v^2}{2g} \tag{13}$$

But, applying equations (14) and (15),

$$Q = \frac{\pi d^2}{4}v \tag{14}$$

$$v = \frac{4Q}{\pi d^2} \tag{15}$$

$$h_{loss} = \frac{kLQ^{1.85}}{C^{1.85}d^{4.87}} + \Sigma K\frac{8Q^2}{g\pi^2 d^4} \tag{16}$$

$$h_{loss} = \frac{kLQ^{1.85}}{C^{1.85}d^{4.87}} + \Sigma K\frac{0.08273Q^2}{d^4} \tag{17}$$

The Total Head Loss (System head loss) h_{loss} is determined in (17).

The experimental unit's system head curve was calculated and plotted as below (Figure 9):

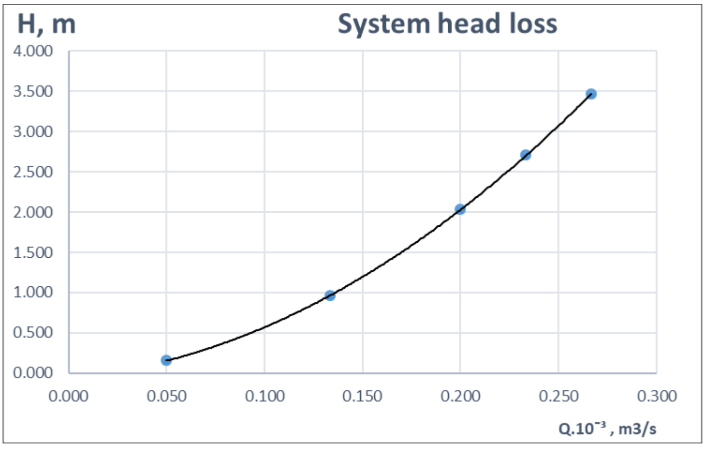

Figure 9. System head curve

Important conclusions from the Hazen-Williams Equation are that pipe length, liquid flow rate, and pipe diameter play an important role in pressure loss in the pipe system.

L – Length: The longer the pipe is, the more pressure loss.

Q – Flow rate: The higher the flow rate, the more pressure loss.

d – Pipe diameter: The wider the pipe diameter, the less pressure loss.

Conclusions and summary

As a result of the bench exercises with the experimental unit, we can confirm our expectation that it provides students with a logical and orderly method to follow when applying the theory that has been discussed in fluid mechanics. Then, example problems are solved using principled methods to clarify their applications. In addition, solving problems with the experimental unit offers students an excellent means of preparing for exams and they can be used later to prepare for marine engineering.

NOTES

1. Conforto s.r.l. Water Pumps. Products. Available from: https://conforto.it. [Viewed 2023-06-12].
2. ELMARK**.** 423433P - Technical Specification EN. Available from: https://bg.elmarkstore.eu. [Online] 2022. [Viewed 2023-06-12].

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