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Parameters Affecting The Efficiency Of A Hydram Pumping System

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ABSTRACT: In the recent studies done on the investigation of the parameters influencing the hydram's pumping efficiency it was revealed that there were some other dimensionless parameters like (P_o / P_z) and (V_s / V_d) which were also found to influence the hydram's pumping efficiency apart from the previously known ones which are (h_3 / H) and (q / Q). This work had also established the usefulness of the basic operational parameters of a hydram water pumping system for predicting its pumping performance than before.

Keywords: Hydram; air vessel; waterhammer; air chamber pressure; delivery flow ; efficiency

1 INTRODUCTION

In a hydram water pumping system there are some energy losses which tend to reduce the useful energy component and this occur due to the pipe flow friction and also the flow acceleration. A ratio of the useful energy to the input energy constitutes the efficiency of the system. For several decades, an air vessel has been used as one of the vital components believed to improve the pumping efficiency of a hydram water pumping system (Rajput 2009, Ojha *et al.* 2011), Krol, (1976) and Parmakian, (1963). Based on the above belief there had been no comprehensive information availed to reveal analytically the clear contribution of an air vessel in the improvement of the hydram's pumping efficiency. In the past it was also believed that air vessel was an essential component in a hydram pumping system but at the recent invention, a Bamford ram (Bamford 2002) had disapproved that belief. However, still the aspect of an improved efficiency in a hydram's pumping system is of utmost importance and desirable because it has such advantages as making the system draw less driving water from a limited water supply resource and also making the reduction in the sizes of the various hydram components including the drive pipes where the latter leads to the advantage of reducing the total cost of the system. In this study, the main objective was primarily focused on the identification of the crucial operational parameters in a hydram's pumping system which could influence its pumping efficiency. The fulfillment of this objective was then tackled by conducting a detailed analysis of the operation of a conventional hydram pumping system by setting a model shown in Figure 1. Both theoretical and experimental analytical studies were critically conducted to explore at large, the effects of the various parameters suspected to influence the efficiency of the system and a summary of analysis is presented in the forthcoming sections.

2 LITERATURE REVIEW AND ANALYSIS

2.1 HYDRAM'S EFFICIENCY

The efficiency of a hydram's pumping system has for many years been defined as the ratio of the output hydraulic energy to the input hydraulic energy and customarily determined by the D'Aubuisson's efficiency model where $\eta = \frac{qh_3}{QH}$ (Tacke, 1987). In the latter, q is the output delivery flow rate, Q is the input drive flow rate, h_3 is the delivery head and H is the input drive head. This expression which is commonly used to determine the hydram's pumping efficiency has such quantities as q, and Q which are actually determined by the basic system's operating variables like L, H, f and A_1 where L is the length of drive pipe, f is the hydram's beat frequency and A_1 is the cross section area of the drive pipe. The above mentioned delivery head h_3 is a total lifting head and this includes the total flow losses. As can be configured, it may not be easy to estimate the total head losses without knowing the various elements contained in the system which are causing such head losses. The later requires an exposure to a physical system. Hence before using the D'Aubuisson's efficiency model, several issues needed to be resolved first in order to eliminate much of the guessed and erroneous data. In so doing, a conventional hydram pumping system model shown in Figure 1 was established where an air vessel was placed as an essential part of the system's components and this was then subjected to a critical analysis. In the model, the pressure P_z was created at the air chamber of the air vessel and this measured the maximum pressure of the system which was then responsible for providing the maximum head for the delivery flow. This pressure was then studied by analyzing the momentum of the flow of the system in between the drive pipe and the air vessel. According to the Daugherty and Franzini (1977), such momentum was expressed by the relationship:

$$\sum Fdt = d(mv) \quad (1)$$

The expansion of Equation (1) when based on the model parameters had resulted in the following expression :

$$A_1(P_a + \gamma H - \gamma h_f - P_z - Y_z\gamma)dt = (m + dm)(v + dv) - mv \quad (2)$$

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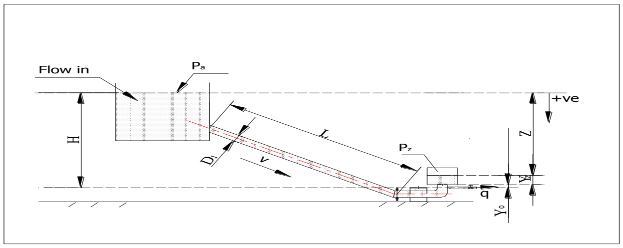

Fig.1: *A setup model for a conventional hydram pumping system.*

Where: A_1 = cross section area of the drive pipe, H = drive head, h_f = frictional head losses in the drive pipe, P_z = instantaneous pressure at the air chamber, Y_z = height of water column in the air vessel, P_a = atmospheric pressure, m = mass of water in the drive pipe, dm = small mass of water in the air vessel and v = velocity of flow in the drive pipe. By making further improvements on Equation (2) where the substitutions like (H – Y_z) = Z and hf = βv^2 were made, the results became:

$$\frac{L}{g}\frac{dv}{dt}=\left(Z+\frac{P_a}{\gamma}\right)-\left(\frac{P_z}{\gamma}+\frac{A_s}{A_1}\frac{v}{g}\frac{dz}{dt}+\beta v^2\right) \qquad (3)$$

From Equation (3), it could be noted that when the system is operating, there must be an equilibrium between the acceleration head $(\frac{L}{g}\frac{dv}{dt})$ which occurs in a drive pipe and the net head on the right hand side of the Equation (3) which is denoted as $\left(Z+\frac{P_a}{\gamma}\right)-\left(\frac{P_z}{\gamma}+\frac{A_s}{A_1}\frac{v}{g}\frac{dz}{dt}+\beta v^2\right)$. The term $\left(Z+\frac{P_a}{\gamma}\right)$ is expressing the available total drive head of the system while the term $\frac{P_z}{\gamma}$ is an air chamber pressure head and the quantity ($\frac{A_s}{A_1}\frac{v}{g}\frac{dz}{dt}$) is a head due to the water column filling the air vessel. The component (βv^2) is the frictional head loss occurring in the flow path. Since the head $\left(Z+\frac{P_a}{\gamma}\right)$ should remain constant for a particular installation set up because the drive head H is set to be constant, logically when the changes in the system equilibrium occur, they will mainly be caused by the variations of the other terms of the equation. A further re-arrangement of Equation (3) including a substitution of the flow rate q in place of the velocity v and also a replacement of the cross section area A_s of an air vessel with the volume V_s of a cylindrical air vessel where $A_s = V_s / h_s$ when h_s is the vessel height, had resulted into the following expression:

$$\left(\frac{P_z}{\gamma}\right)=\left(Z+\frac{P_a}{\gamma}\right)-\left(\frac{\beta q^2}{A_1^2}+\frac{L}{g}\frac{dv}{dt}+\frac{V_s}{h_s A_1^2}\frac{q}{g}\frac{dz}{dt}\right) \qquad (4)$$

Thus from the above deduction, it could be revealed that the pressure head (Pz/ γ) was one of the important parameters which could be used to control or regulate both the acceleration of the flow and delivery flow rates and these were the quantities influencing the overall performance of the hydram's pumping system.

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2.2 THE ALTERNATIVE STUDY OF EFFICIENCY IN A HYDRAM'S PUMPING SYSTEM BY USING THE DIMENSIONAL ANALYSIS METHOD

In this approach all elements suspected to influence the efficiency of the system including the exposed ones in Equation (4) were listed as the variables of the efficiency E_v as shown in Equation (5).

$$E_v=\Phi\left(P_z,q,h_3,f,L,H,P_o,V_s\right) \qquad (5)$$

In order to filter out the appropriate parameters influencing the efficiency, a dimensional analysis methodology was applied with the use of a **Pie Theorem** (Cengel *et al.* 2010). According to this theorem, the total number of variables n involved in Equation (5) is 9 and the number of basic dimensions m = 3 and these are M, L and T. Thus the expected number of dimensionless groups (π_i) = n – m = (9 – 3) = 6. In this dimensional analysis, the selected repeating variables are P_z with dimension ($ML^{-1}T^{-2}$), q with (L^3T^{-1}) and H with (L) dimensions. Also E_v is a dimensionless parameter with the dimension ($M^0L^0T^0$). Thus π_1 is expressed by the dimensions:

($M^0L^0T^0$) = $(ML^{-1}T^{-2})^a\,(L^3T^{-1})^bL^{c}\cdot(M^0L^0\,T^0)$. Hence,

Analysis of dimensions:

M: a+0 = 0 and hence a = 0.

$$\Pi_1=P_z^a q^b H^c E_v$$

L: -a+3b+c+0 = 0 and hence 3b+c = 0.

T: -2a-b+0 = 0 whereby –b+0 = 0 and hence b = 0.

Substitution of b = 0 into (3b+c = 0) will result into c = 0.

$$\Pi_1=P_z^0 q^0 H^0 E_v$$

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Solution: a = 0, b = 0 and c = 0. Thus:

$$\Pi_1 = E_v$$

And hence

Similarly,

where the dimension for h_3 is (L) and,

$$\Pi_2 = P_z^a q^b H^c h_3$$

$(M^0L^0T^0) = (ML^{-1}T^{-2})^a (L^3T^{-1})^b L^c (L)$.

Solution: a = 0, b = 0 and c = -1. Thus, $\Pi_2 = P_z^0 q^0 H^{-1} h_3$

and hence, $\Pi_2 = \dfrac{h_3}{H}$

Similarly,

$\Pi_6 = P_z^a q^b H^c V_s$ Where the dimension for V_s is (L^3) and

$(M^0L^0T^0) = (ML^{-1}T^{-2})^a (L^3T^{-1})^b L^c (L^3)$.

Solution: a = 0, b =0 and c = -3. Hence,

$$\Pi_6 = P_z^0 q^0 H^{-3} V_s$$

$$\Pi_6 = \frac{V_s}{H^3}.$$

Also the π_i groups could be modified by re-writing the π_i as $\boldsymbol{\pi_i^a}$ such that the index **"a"** could acquire a positive, negative or a fraction number to suit the aspired application situation (Cengel *et al.* 2010). Also the substitution of some relevant application variables was allowed provided that their dimensions were correctly matched. The following modifications were then made:

1) Π_3 was transformed from $\Pi_3 = \dfrac{H^3 f}{q}$ to $\Pi_3^{-1} = \dfrac{q}{Q_t}$

and $\Pi_{3\text{mod}} = \dfrac{q}{Q_t}$

whereby Q_t represented the input drive flow rate and q the delivery flow rate.

2) $\Pi_6 = \dfrac{V_s}{H^3}$

3) Π_6 was transformed from to

$$\Pi_{6\text{mod}} = \frac{V_s}{V_d}$$

Where by V_d represented the pumped discharge volume per cycle and V_s is the air vessel volume. Since $\pi_1 = \phi(\pi_2, \pi_3 \ldots \pi_6)$, the efficiency E_v could thus be expressed as a function of several dimensionless parameters which are shown in Equation (6) whereby :

$$E_v = \Phi\left(\frac{P_o}{P_z}, \frac{h_3}{H}, \frac{L}{H}, \frac{V_s}{V_d}, \frac{q}{Q_t}\right) \quad (6)$$

3 RESEARCH METHODOLOGY

In this work, the dimensionless parameters obtained in Equation (6) were subjected to the critical studies and followed by the experimental studies. In establishing the experimental data for the analysis presented in Equation (6), the guidelines set by Montgomery, (Montgomery, 2001) were applied. The next step was to design an appropriate experimental rig to study the characteristics of efficiency against the effects of the above mentioned dimensionless parameters. In this case a hydram testing rig capable of allowing the measurements of such data as P_o, P_z, h_3, H, L, f, V_d, V_s, q and Q_t was designed and fabricated as sketched in Figure 1. In the rig, the pressures were measured with the use of the pressure transducers and recorded by a computerized data logging system. The beat frequency f was acquired by taking the average time taken by a sample of operation cycles per time in seconds. The air vessel sizes V_s were made as unit specimens bearing the various capacities like 0.12, 4.9, 9.8,14.6 and 19.6 litres. The calibration of the pressure transducer was done by mounting one of the transducers onto a specially designed pressure tight piped system. This pressurized air of known pressure in bar units was filled into the calibration unit from the air compressor. The calibration results had shown that a reading of 0.0 bar corresponded to an electrical current of 4.0 mA. The intermediate readings were also taken. After plotting the data of the pressure against the generated electrical current, a correlation trend having a linear relationship was achieved. In general the calibrated data was found to agree well with the supplied manufacturer's information and this gave us a go ahead for using the transducers in the further planned experiments. After the calibration process, the next step was to conduct trial runs of the system and making any necessary adjustments for its proper performance and measurements. Eventually a set of 9 experimental runs were then conducted on the rig and the data obtained was prepared in the form of a matrix data as listed below:

The summarized matrix data for E_{vf}:

Parameters

1 V_s / V_d

2 P_z / P_o

3 h_3 / H

4 L / H

5 q / Q_t

6 $Y10 = E_{vf}$

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4 RESULTS AND DISCUSSIONS

The outcome of the acquired experimental data has been presented in a graphical form shown in Figures 2 to 5. In Figure 2, there was an emerging relationship between the efficiency E_{vf} and parameter h_3/H whereby the trend presents a curve. The value of h_3/H which matches with the peak efficiency was 12.5. Also in Figure 3 it could be seen that there was a relationship between the efficiency E_{vf} and parameter P_o/P_z which was presented by a curve. The graph attained its peak efficiency at the ratio $P_o/P_z = 0.4$. Similarly in Figure 4, a plot of E_{vf} versus V_s / V_d had shown a relationship with a curve trend and whose peak efficiency occurred at value of $V_s / V_d = 3500$. Figure 5 showed that the plotted data of E_{vf} versus q / Q_t was also having a curve trend whose peak efficiency occurred at the value of $q/Q_t = 0.045$. Although the parameter L/H was mentioned earlier to be a parameter affecting the efficiency E_{vf}, its behaviour against E_{vf} was not presented in this study because the variable L was set to be a fixed value throughout the experiments done.

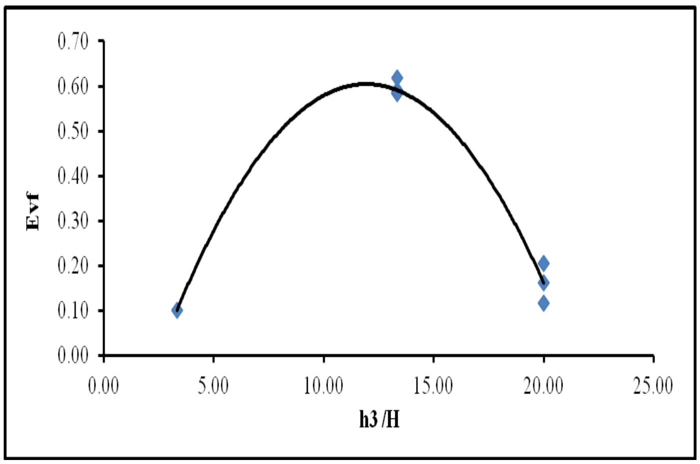

Figure 2: *Behavior of E_{vf} versus h_3/H when H = (1.5 – 6) m, f = (30 – 120) beats /min, V_s = (2.45 – 19.6) litres, h_3 = (20 – 120) m and L = 18.5 m*

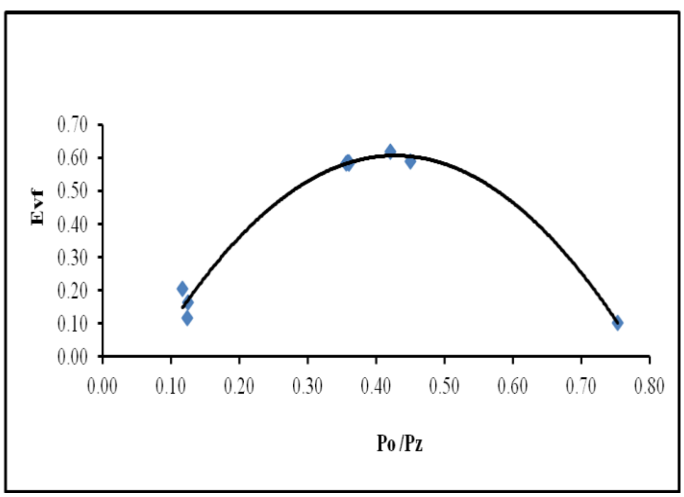

Figure 3: *Behavior of E_{vf} versus P_o/P_z when H = (1.5 – 6)m, f = (30 – 120) beats /min, V_s = (2.45 – 19.6) litres, h_3 = (20 – 120) m and L = 18.5 m*

The achieved results in this study were also compared with the previous investigations done by the other researchers like Gupta *et al*. (1999) and Rajput (2009). These two researchers had previously found that the hydram's efficiency was influenced by such dimensionless parameters as:

$$\left(\frac{h_3}{H}, \frac{L}{H} \text{ and } \frac{q}{Q_t}\right)$$

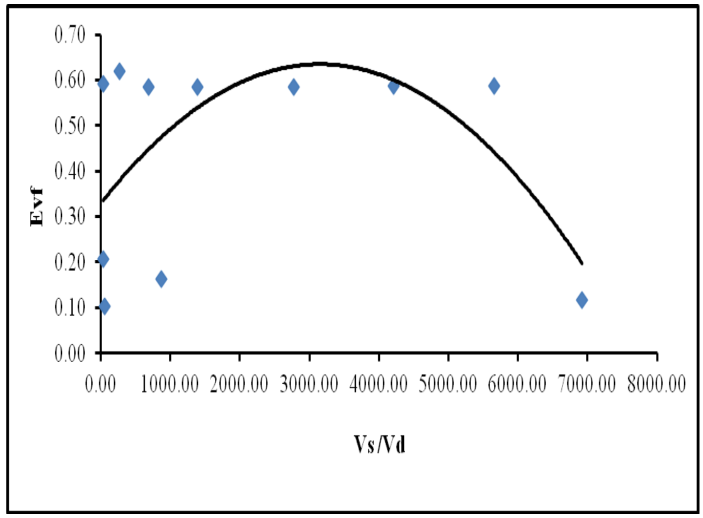

Figure 4: *Behavior of E_{vf} versus V_s / V_d when H = (1.5 – 6) m, f = (30 – 120) beats /min, V_s = (2.45 – 19.6) litres, h_3 = (20 – 120) m and L = 18.5 m*

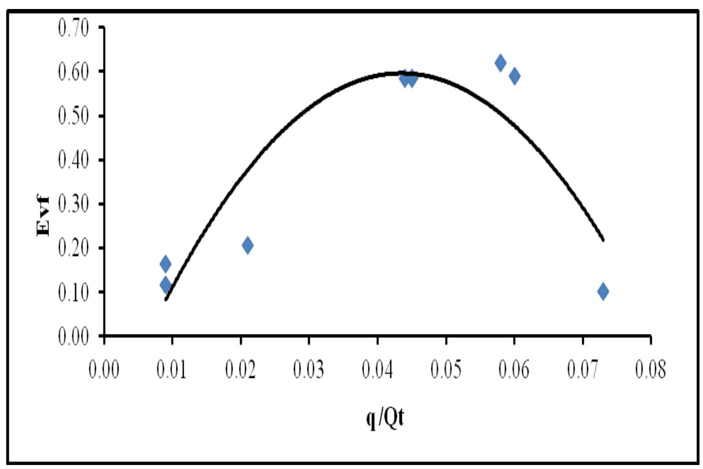

Figure 5: *Behavior of E_{vf} versus q / Q_t when H = (1.5 – 6) m, f = (30 – 120) beats /min, V_s = (2.45 – 19.6) litres, h_3 = (20 – 120) m and L = 18.5 m*

Since the D'Aubuisson's efficiency model was based on such parameters as h_3 / H and q / Q_t it implied that the parameter L / H was an additional one. Likewise in this recently done work five dimensionless parameters were identified to influence the hydram's pumping efficiency whereby those above three mentioned ones were also in the list. Hence the other two parameters which are (P_o / P_z) and (V_s / V_d) and which had clearly shown to be related with the hydram's pumping efficiency were regarded as the additional parameters now adding up on the previously known list of the three ones. From these latter pa-

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rameters it is clearly visible that some of these parameters are directly related with the air vessel. For example V_s is the volume of an air vessel. P_z is the pressure at the air chamber of an air vessel. P_o is the initial pressure at the air chamber of air vessel. Its only the volume V_d which is the volume of the pumped water per cycle which is not related to the air vessel. It is from this perspective view we now see that the existence of an air vessel in a hydram water pumping system can contribute effectively in the improvement of the hydram's pumping efficiency. In this study the smallest air vessel specimen used was having a volume of 0.12 litres. This was nearing a zero volume air vessel and was purposely placed in the list in order to seek the needed answers on the challenges now existing obout the hydrams operating without having the air vessels. From the experimental results, it was realized that this smallest air vessel had relatively presented the lower efficiencies and the major reason for its poor efficiency was due to having an insufficient air in its air chamber which was necessary for the proper performance of an air vessels. This deduction is also found to agree with the emphasize placed by Bamford, (Bamford, 2002) on his hydram which is not having an air vessel that, the air vessel cells were still required whenever better efficiencies were required. This implied that such pumps had low efficiencies and that's why the air vessel cells were required.

5 CONCLUSION

In the study of the efficiency on the hydram's pumping system whereby an air vessel is coupled to such system, there were several dimensionless parameters found to influence the efficiency even beyond those attributed by the D'Aubuisson's efficiency model. Two dimensionless parameters which were (P_o / P_z) and (V_s / V_d) were added in the previously known list. The study had therefore proved beyond no doubt that the air vessels were still required whenever improved efficiencies were required in any hydram water pumping system.

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