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DESIGN AND HYDRAULIC PERFORMANCE OF A NOVEL HYDRAM

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Abstract: The hydram is a self-operating water-lifting device without other external energy, such as electricity and fossil fuel. The structure of a hydram not only affects its appearance and weight, but also plays an important role in the hydraulic performance. A novel design for the hydram body was presented, which adds a short cambered diffuser between the elbow and the waste valve in the hydram while canceling the inlet diffuser that is a necessary part in the traditional hydram. The advantages of the novel design are more compact in structure, lighter in weight and less in composite resistance coefficient. The tests were conducted on a 100 mm novel hydram. The minimum of the composite resistance coefficients is about 1.85. While the supply head is between 2.0m and 2.2m, the new hydram can lift water to above 100m and its efficiency is between 53% and 64% when the delivery head is under 50m. If the supply head is between 1.5m and 1.7m, the new hydram can lift water to above 70m and its efficiency ranges from 50% to 59% when the delivery head is below 45m. While the supply head varies between 1.1m and 1.2m, the new hydram can lift water to above 50m and its efficiency is between 50% and 58% when the delivery heads is under 40m.
Key words: Hydram, novel body, cambered diffuser, hydraulic performance and test

The hydram, hydraulic ram pump, is an automatic water-lifting device, which utilizes the kinetic energy in a moving column of water to raise part of that water to a higher level, owing to the water hammer effect generated by the cyclic opening and closing of two check valves (waste and delivery valve). The advantages are: 1) the device is environment friendly and operates without other external energy, such as electricity and fossil fuel; 2) the efficiency of a well-made hydram ranges from 50% to 75%(Lansford and Dugan[1]; Watt[2]), yet that of a pump-motor unit below 3kw does not exceed 50%; 3) the operational maintenance is easy and the service life is long because the moving parts are only two check valves. It is reported that a hydraulic ram pump has been working over 100 years and is on service now.

A hydram water supply system generally consists of the upper and lower reservoirs, drive and delivery pipes, the storage tank and the hydram, as shown in Fig.1,

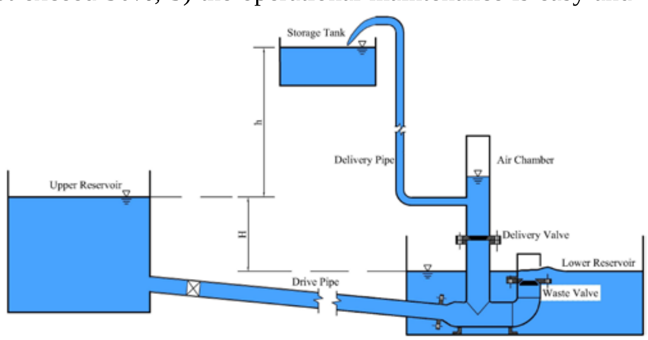


Figure 1. Hydram water supply System

Where H is the supply head, or the difference between the water level of the upper reservoir and that of the lower reservoir; and h is the delivery head, or the difference between the water level of the storage tank and that of the upper reservoir.

It is reported that the first hydram was built by Whitehurst (1772), which was able to lift water to a height of 4.9m. However, it was operated manually through opening and closing the stopcock. The first automatic hydram was invented by Montgolfier(1796)for raising water to his paper mill. Pierce (1816) improved the pump through introducing the air or snifter valve to compensate the air dissolved in water and his pump which is 300 mm in diameter is reported to pump 1700l/min to a height of 48m. So far, there are some different types of the hydrams which are worldwide used. The design of hydrams has been developed and perfected in the past 200 years. Consequently, the performance of hydrams could be predicted(Schillearn and Kahangire[3]; Young[4]), including the efficiency, delivery head and flow, and the frequency in which the waste valve or delivery one opens or closes. Yet the structure of the hydram bodies have not changed much and the research on the hydraulic performance of the different body structure was rare.

The objectives of this article is to present the design of a novel hydram body and then to do the tests for measurement of its hydraulic performance.

Design of novel hydram body

In order to achieve a satisfactory hydraulic performance, in the design of a hydram body not only its passage is required to be smooth, but also the influence of the waste valve disc on reduction of the flow cross section should be taken into account. Thus, the designed parameters of a hydram body (Hua and Yang[5]) should meet

$$A_1 - A_d \geq A = A_0 \tag{1}$$

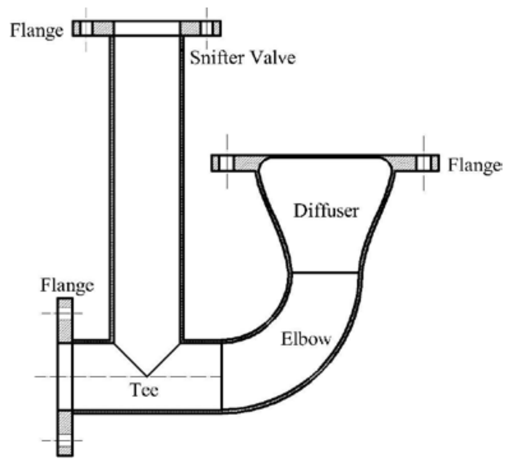


Figure 2. Structure of novel hydram body

Where A is the cross-sectional area of the drive pipe, A_0 is the orifice area of the waste valve, A_1 is the cross-sectional area of the diffuser outlet, and A_d is the area of the waste valve disc.

The novel hydram body designed herein is shown in Fig.2, which consists of a straight tee, a 90^0 diameter elbow, a diffuser and flanges. The characteristic parameters are

$$A_1 - A_d \geq A = A_t = A_b = A_0 \tag{2}$$

Where A_t is the cross-sectional area of the tee and A_b is the cross-sectional area of the elbow.

The diffuser increases the cross-sectional area of the hydram body from A to A_1. Commonly, the conical and cambered diffusers may be chosen.

The average velocity decreases as the cross-sectional area increases while the diffused angle, α, is lower than the certain value. The local resistance coefficient of the diffuser is much less than that of a pipe at the same length, whose cross-sectional area is equal to that of less side of the diffuser. For the diffuser with a certain length, while the diffused angle exceeds the critical value, the local resistance coefficient will increase greatly as the angle does, even many times greater than that of a straight pipe. The main reasons are the severe turbulent fluctuation, boundary layer separation from the diffuser wall and vortex induced.

When α is less than 40^0, flow does not separate from the entire part of the diffuser, instead, it separates from the position where the velocity is slower than the other parts of the cross-section for asymmetric structural parameters and velocity profile. Provided that flow separates from the certain wall, the flow separation will not take place while the increase of static water pressure along the conical diffuser weakens or even ceases. For the reason, the velocity distribution on the cross-section of the conical diffuser is asymmetric, which leads to the asymmetric pressure distribution on the waste valve disc. Thus, the friction between the leader and sleeve of the waste valve will increase.

When α is between 4^0 and12^0, the local resistance coefficient of the conical diffuser, related to the diffusance Ψ ($\Psi = A_1 / A$), will be minimum. The smaller Ψ is, the bigger α with respect to the least local resistance coefficient is. However, the hydram body should be compact in structure so that the length of the diffuser is as short as possible. So, the short diffuser with large diffusion angle is advised.

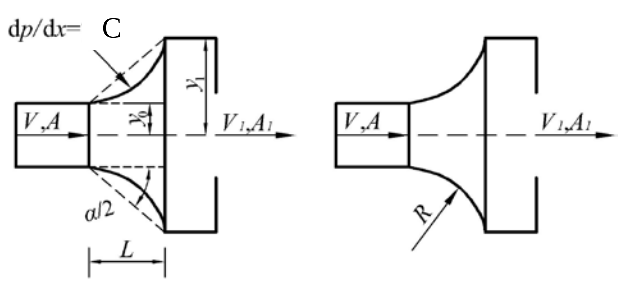
In conclusion, the conical diffuser should not be used in the design of the novel hydram body.

As shown in Fig.3, the cross-sectional area of a cambered diffuser grows in the inlet part much less than in the outlet part and the pressure gradient changes smaller, which makes the flow separation be weakened and the head loss be reduced. If the pressure gradient, $\mathrm{d}p/\mathrm{d}x$,along the diffuser is constant, the structure must be perfect. While α is between 25^0 and 90^0, the local resistance coefficient of a cambered diffuser will be less 40% than that of a conical diffuser. In this range, the bigger α is, the more the local resistance coefficient of a cambered diffuser reduces. While α is between 15^0 and 20^0, the head loss of a cambered diffuser is even greater than that of a conical one. So, it is reasonable that the cambered diffuser is used only with a big angle.

When $\mathrm{d}p / \mathrm{d}x$ is constant, the generatrix equation of a cambered diffuser is

$$y = \pm \frac{y_1}{\sqrt[4]{1 + \left[\left(\frac{y_1}{y_0} \right)^4 - 1 \right] \frac{x}{L}}} \tag{3}$$

Where y_1 is equal to half of D_1, y_0 is equal to half of D that is the inlet diameter, D_1 is the outlet diameter, L is the length, x is the distance from the inlet of the diffuser and $|y|$ is radius of the cross-section at x.



(a) dp/dx=C (b)Arc

Figure 3. Cambered diffuser

When $\mathrm{d}p/\mathrm{d}x$ is constant and A/A_1 ranges from 0.1 to 0.9, the local resistance coefficient of a cambered diffuser can be calculated by

$$\xi_d = \frac{\Delta p}{\rho V^2/2} = \phi \left(1.43 - 1.3 \frac{A}{A_1} \right) \left(1 - \frac{A}{A_1} \right)^2 \tag{4}$$

Where ξ_d is the local resistance coefficient, Δp is the pressure difference between the inlet and outlet, V is the velocity at the inlet of the diffuser, ρ is the water density and φ are coefficients related to the relative length of the diffuser, shown in Table 1.

Table 1. Relationship between φ and L/D_1

L/D_1	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
φ	1.02	0.75	0.62	0.53	0.47	0.43	0.40	0.38	0.37

The local resistance coefficient of a diffuser that the generatrix is arc is much less than that of a conical one, seen in Fig.3 (b). As the cambered diffusers have been standardized and commercialized, the cambered diffuser is used in the design of the novel hydram.

A typical traditional hydram body usually consists of an inlet diffuser, a tee, an elbow and flanges, shown in Fig.4. The parameters meet

$$A_1 - A_d \geq A = A_0 \text{ , } A_t = A_b = A_1 \tag{5}$$

Generally, the passage length of a hysram body is much shorter than the drive pipe. Thus, the major head loss of the body is the local head loss and the frictional head loss can be neglected.

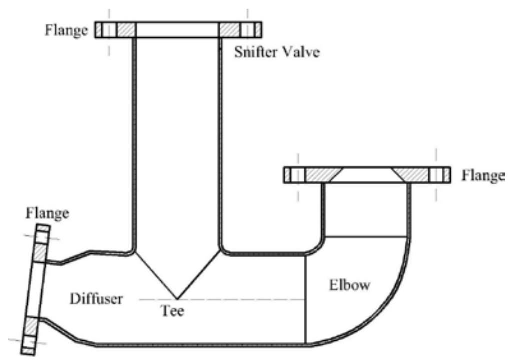


Figure 4. Structure of traditional hydram body

For the novel hydram, the composite resistance coefficient results from the elbow, cambered diffuser and waste valve when the delivery valve is closed. Because they are connected directly, the vortexes induced will affect mutually, reducing the composite resistance coefficient. For a traditional hydram, the composite resistance coefficient is caused by the inlet diffuser, elbow and waste valve when the delivery valve is closed. As the distance between the inlet diffuser and the elbow is relatively large, the inter-effect of the vortexes induced is weak. So, if the novel hydram and traditional one are same not only in the local resistance coefficients of the elbow and waste valve, but also in those of the inlet diffuser and cambered diffuser, the compsite resistance coefficient of the traditional hydram may be slightly greater than that of the novel one.

Moreover, if a traditional hydram and a novel one are the same in material and $A_d = A = A_0$, then for the former there is $A_{tc} = A_{bc} = A_{1c} = 2A$ and for the latter there is $A_{1n} - A_d \geq A = A_{tn} = A_{bn} = A_0$, in which the subscript 'c' and 'n' represents the traditional hydram and the novel one , respectively. As a result, $A_{tc}/A_{tn} = A_{bc}/A_{bn} = 2$, $d_{tc}^2/d_{tn}^2 = d_{bc}^2/d_{bn}^2 = 2$ and $d_{tc} = d_{bc} = d_{bc}^2/d_{bn}^2 = \sqrt{2}d_{tn} = \sqrt{2}d_{bn}$. Thus, the weight of the traditional body is $\sqrt{2}$ times as great as that the novel one. In practice, under a given water hammer pressure, the wall thickness of the novel body may be less than that of the traditional body because the diameter of the former may be less than the latter. That is important for a large-scale hydram in lowering the sizes, weight, transport cost and civil engineering investment.

To sum up, compared with the traditional hydrams, the design of the novel hydram body has the strong points that are more compact in structure and is lighter in weight and less in composite resistance coefficient.

Design example

The parameters of the novel hydram to be designed are that the inner diameters of the straight tee and 90^0 diameter elbow are 100mm, the orifice diameter of the waste valve is 100mm and its sealing surface is 45^0 cone and 10mm wide, and the diameter of the discharge valve disc D_d is 120mm .

Based on Eq. (2), the following relationship can be derived

$$A_1 \geq A_d + A = \pi \frac{D_d^2}{4} + \pi \frac{D^2}{4} = 19163.7\left(\mathrm{m}^2\right)$$

Therefore, the inner diameter of the diffuser, $D_{1,}$ should be greater than 156.2mm. A commercial cambered diffuser, also known as increaser, is used. Its parameters are the inlet diameter D=100mm, the outlet diameter D_1=200mm, the length L=152mm, and the diffusion angle $\alpha = 36.4^0$ which meets the condition that α is between 25^0 and 90^0.

Since A/A_1=0.25, the resistance coefficient of the diffuser can be calculated by Eq. (4). Let $c = L/D_1$, then the diffuser considered has L/D_1=0.76. According to Tab.1, φ equals 0.65 that is derived by using the linear interpolation. Thus, the local resistance coefficient of the diffuser is

$$\xi = \varphi\left(1.43 - 1.3\frac{A}{A_1}\right)\left(1 - \frac{A}{A_1}\right)^2 = 0.65\left(1.43 - 1.3 \times \frac{1}{4}\right)\left(1 - \frac{1}{4}\right)^2 = 0.4$$

Model tests

The tests were conducted in the lab of China Institute of Water Resources and Hydropower Research. The hydram water supply system is shown in Fig.5. The inner diameters of the tee and 90^0 elbow all are 100mm. The cambered diffuser is a commercial increaser, whose inlet and outlet diameters are 100mm and 200mm, respect-tively, and whose length is 152mm. A pressure sensor is set between the tee and elbow. Another pressure sensor is set on the bottom of the air chamber. A water-level sensor is set inner the air chamber.

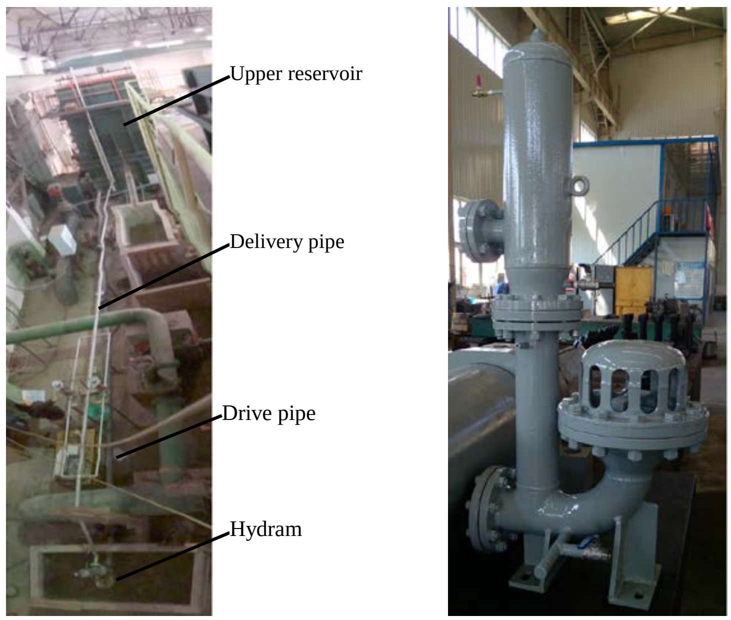


Figure 5. Layout of hydram water supply system

The drive pipe is 13m in length and 0.1m in inner diameter , through which water flows from supply reservoir into the hydram. A butterfly valve is installed on the inlet side of the drive pipe and an electromagnetic flow meter is installed in the middle of the drive pipe to measure the flow. The water level of the supply reservoir is measured by a pressure sensor and a piezometric tube.

The delivery pipe is 17m in length and 0.05m in inner diameter, through which water flows into the supply reservoir again. There is an electromagnetic flow meter in the middle of the delivery pipe. To simulate the different delivery heads, the layout of the delivery pipe between the air chamber and the supply tank is from the main to three branch pipes and then to the main. A butterfly valve and two pressure regulator valves are placed in the three branch pipes, respectively. Taking the measures, the delivery head can be controlled between 5m and 120m. One of the pressure regulator valves ranges from 30m to 70m in water pressure and the other from 80m to 120m.

The lower reservoir where the hydram is placed is 2m long, 1.5m wide and 1m high. A gate is fixed on a side of the reservoir. A triangular thin-plate weir is used to calibrate the electromagnetic flow meter in the drive pipe. The measured flows with the triangular thin-plate weir and with the electromagnetic flow meter are listed in Table. 2, the error between the two is less than 5%.

Table 2. Measuring results of triangular thin-plate weir and electromagnetic flow meter

Flow of electromagnetic flow meter (l/s)	13.95	11.02	8.96	7.79	6.49	4.95	4.15	2.88	2.03	1.06
Flow of triangular thin-plate weir (l/s)	14.53	11.35	9.20	7.95	6.64	5.04	4.23	2.94	2.06	1.07
Error (%)	4.2	3.0	2.7	2.1	2.3	1.8	1.9	2.1	1.5	1.0

As the electromagnetic flow meter in the delivery pipe can't take the accurate measurement for the small flows, the delivery flow is measured by the weighing method. Water is collected by 60L and 160L buckets and measured by a 300kg platform scale. Water collected is heavier than 200kg, or time is longer than 600s.

The measuring apparatus are listed in Table.3.

Table.3 Measuring apparatus

Apparatus	Position	Measuring Range	Accurancy
Electromagnetic flow meter	Drive pipe	0-20L/s	
Pressure sensor	Air chamber	0-1.6MPa	
Pressure sensor	Hydram body	0-2.0MPa	
Pressure sensor	Supply reservoir	0-50KPa	
Pressure sensor	Wasted pool	0-50KPa	
Water-level sensor	Air chamber	0-500mm	
Platform scale		0-300kg	

The relationship between the waste valve stroke, S_v, and the composite resistance coefficient, ξ, of the elbow, cambered diffuser and waste valve is shown in Table.4. While S_v is between 30mm and 40mm, ξ is less and equals 2.39 to 1.85. Usually, the maximum stroke of waste valve is set to be $S_{vmax} \approx D_0/4$ in which D_0 is the orifice diameter of the waste valve. The tests verified for the novel hydram that the delivery flow and efficiency were greater when S_{vmax} =30mm > D_0 /4=25mm and ξ =2.39. As comparison, in Table.4 are also listed the parameters of the waste valve in 53mm Wilcox hydram[6], in which ξ_w is only the local resistance coefficient of the waste valve, the maximum stroke is suggested to be S_{vmax} =12mm < D_0 /4=13.25mm and ξ_w =2.5.

Table.4 Relationship between resistance coefficients and waste valve strokes

100mm novel hydram		53 mm Wilcox hydram		
S_v(mm)	ξ	S_v(mm)	ξ_w	
5	37.12	8	6.2	
10	11.45	10	3.7	
15	6.31	12	2.5	Suggested

20	3.89		14	1.75
25	2.99		16	1.37
30	2.39	Suggested		
35	1.85			
40	1.89			

It is noticed that, if the elbow and diffuser are considered, the composite resistance coefficient of Wilcox hydram may be greater than that of the novel hydran in the same conditions. The local resistance coefficient of the 90^0 short diameter elbows for commercial is about 0.26 and that of the short diffuser is about 0.4 calculated in section 2. If taking those values for the elbow and diffuser in 53mm Wilcox hydram, then its minimum composite resistance coefficient $\xi_{\min} = 1.37 + 0.26 + 0.4 = 2.03$, which is greater than that of the novel hydram, $\xi_{\min} = 1.85$.

The measured results are listed in Table.5, in which the maximum waste valve stroke is 30mm. $Q = Q_d - q$ is the mean waste flow, where Q_d is the flow measured in the drive pipe and q is the mean delivery flow. H is the mean supply head. $h = H_{pi} - H_{si}$ is the mean delivery head, in which H_{pi} is the piezometric head at the bottom of the air chamber and H_{si} is the water stage of the upper reservoir. η is the efficiency and N is the frequency that is the times of opening or closing the valve per minute.

Q, H, q and η are computed by

$$Q = \frac{1}{T}\sum_{i=1}^{M} Q_i \Delta t, \; H = \frac{1}{T}\sum_{i=1}^{M} H_i \Delta t, \; h = \frac{1}{T}\sum_{i=1}^{M} h_i \Delta t, \; \eta = \frac{qh}{QH} \tag{6}$$

Where Δt is the time step for measurement, T is the measurement time, Q_i is the instantaneous flow, H_i is the instantaneous supply head, h_i is the instantaneous delivery head.

From Table 5, the conclusions can be made that: While the supply head H is 2.0m to 2.2m and the waste flow Q is 3.8 l/s to 2.0l/s and the delivery head h increases from 5.6m to 101.1m, then the delivery flow q is from 0.80l/s to 0.01l/s, the efficiency η ranges from 63.9% to 26.9% and the frequency N changes from 55 to 45. When the delivery head h is less than 50m, the efficiency η is greater than 53%.

Table.5 Experimental Results of the Novel Hydram

Number	H (m)	Q (l/s)	h (m)	q (l/s)	q (m^3/d)	η (%)	N (times/min)
1	2.01	3.728	5.56	0.803	69.39	59.70	54
2	2.02	3.793	8.59	0.564	48.72	63.39	54
3	2.02	3.636	11.92	0.391	33.80	63.46	54
4	2.03	3.627	15.51	0.303	26.22	63.86	54
5	2.04	3.647	20.07	0.235	20.32	63.41	55
6	2.07	3.308	24.89	0.174	15.05	63.33	51
7	2.09	3.219	27.47	0.149	12.85	60.70	51
8	2.09	3.371	32.52	0.125	10.83	57.92	51
9	2.11	3.029	38.15	0.099	8.56	59.12	50
10	2.15	2.861	41.48	0.087	7.51	58.71	49
11	2.16	2.588	46.17	0.069	5.95	56.85	48
12	2.12	2.411	50.18	0.055	4.71	53.53	47

13	2.13	2.464	56.18	0.041	3.55	44.07	47
14	2.11	2.683	62.24	0.039	3.35	42.65	48
15	2.09	2.729	63.94	0.033	2.87	37.19	49
16	2.09	2.729	65.46	0.031	2.69	35.79	48
17	2.09	2.655	71.64	0.027	2.33	34.89	48
18	2.05	2.530	76.56	0.023	2.00	34.18	47
19	2.09	2.505	80.67	0.022	1.89	33.70	47
20	2.10	2.426	84.59	0.020	1.72	32.93	47
21	2.13	2.164	94.91	0.014	1.25	29.85	46
22	2.15	2.066	98.82	0.012	1.07	27.66	45
23	2.17	1.969	101.08	0.011	0.98	26.90	45

Conclusions

The structure of a hydram body affects not only its appearance and weight, but also its hydraulic performance. A novel design of the hydram body is presented herein.

The novel hydram body consists of a straight tee, a 90° diameter elbow and a diffuser. The conical diffuser is not advised, because it leads to the asymmetric pressure distribution on the waste valve disc. The cambered diffuser will be a good choice and the diffuse angle α is recommended between 25^0 and 90^0.

Compared with the traditional hydram, the novel hydram body is more compact in structure, lighter in weight and less in the composite resistance coefficient. In the same material and composite resistance coefficient, the weight of the new body is only about $1/\sqrt{2}$ times as great as that of the tradition body. It is important for large-scale hydrams in reducing transport cost and civil engineering investment.

From the tests for 100mm new hydram, the conclusions can be made taht: While the supply head is 2.0m to 2.2m and the waste flow Q is 3.8 l/s to 2.0l/s and the delivery head h increases from 5.6m to 101.1m, then the efficiency η ranges from 63.9% to26.9%. When h <50m, η >53%.

References

[1]Lansford, W. M. and Dugan,W.G., “An analytical and experimental study of the hydraulic ram”, *Univ. Of Ill. Bull.*, Vol.38,No. 22, (1941).

[2]Watt, S. B. “*A manual on the hydraulic ram for pumping water*”, Intermediate Technology Development Group Water Development Unit, National College of Agricultural Engineering, Silsoe, Bedford, MK45 4DT, U.K., *(*1985).

[3]Schillearn E. J . and Kahangire P., “Analysis and computerized model of the automatic hydraulic ram pump”, *Can. J. Civ. Eng.* , Vol.11, (1984), pp743-750.

[4]Young B. W., “Simplified analysis and design of the hydraulic ram”, *Proc.* Instn *Mech. Engrs, Part A, Journal of Power and Energy,* Vol.210, (l996),pp295-303.

[5]Hua S.C. and Yang X.L. etc(Translated),“*Fluid resistance manual”*. National Defence Industry Press,Beijing,(1985).

[6]Young B. W. “Design of hydraulic ram pump systems”, *Proc. Instn Mech. Engrs, Part A, Journal of Power and Energy,* Vol.209 ,(l995),pp313-312.