vocational guidance to these fields and provision for effective training in those sciences and skills needed are highly appropriate.

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FLUID MECHANICS OF A ROPE PUMP

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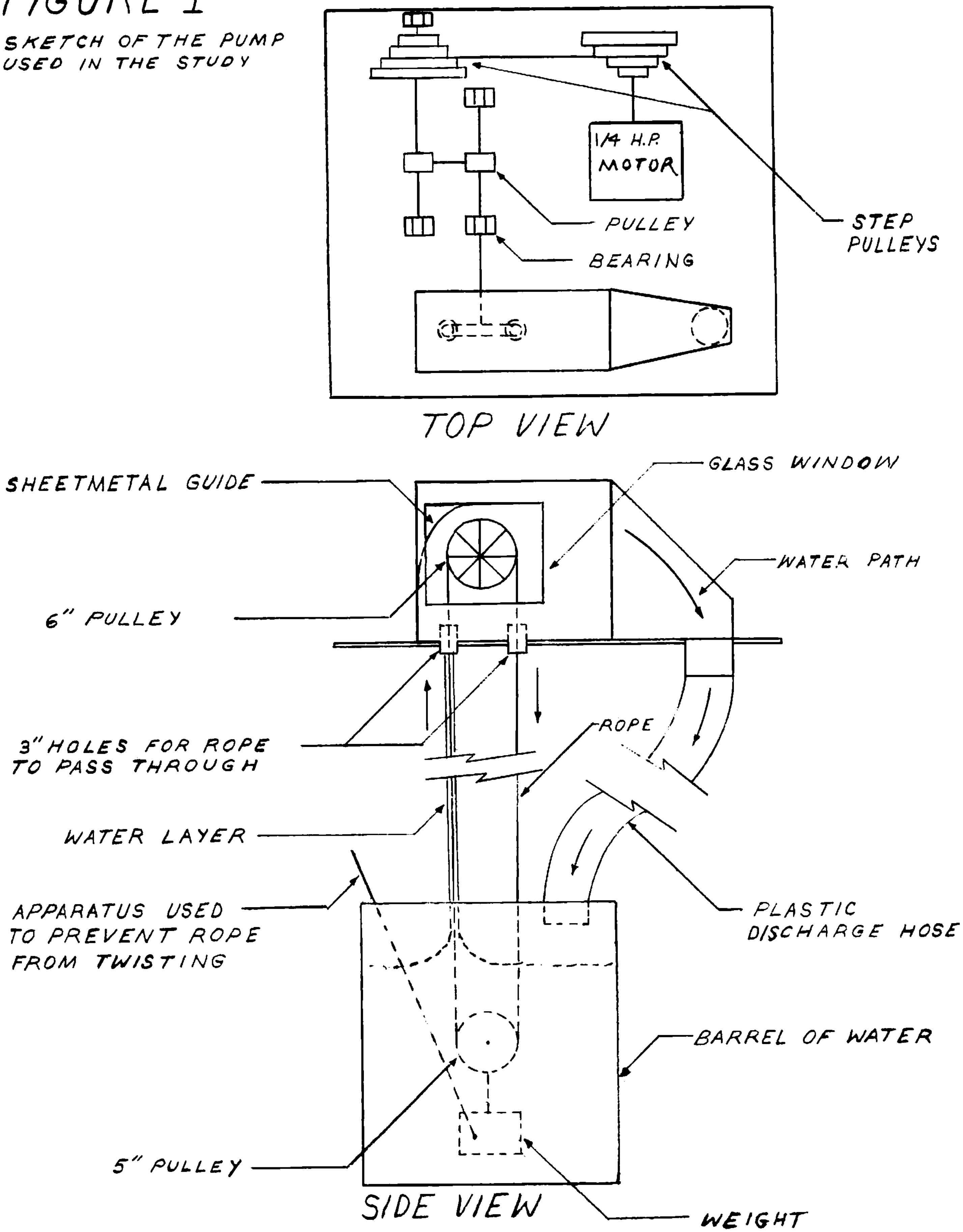
INTRODUCTION

It is possible to raise water vertically by using a continuous rope moving around two pulleys. The lower pulley must be submerged and the water being lifted will be discharged at the upper pulley. Langharr (1) reported that by using cotton clothesline he was able to lift 11 gallons of water per minute through a vertical distance of 25 feet. He used a double pulley driven by an electric motor and two cotton clotheslines. The clotheslines were not enclosed in a tube.

The objectives of the experiments reported

FIGURE 1

SKETCH OF THE PUMP USED IN THE STUDY



here were to study the fluid mechanics of a rope pump and, if possible, to arrive at an equation that would describe the behavior of rope pumps in general, and to determine if rope pumps were effective and efficient enough to have practical applications.

The apparatus used in the experiments described in this paper is shown in figure 1.

ANALYSIS OF THE PROBLEM

From observation of a rope pump built by agricultural engineering students for an exhibit at engineers day and from observations of fluids moving down exposed vertical surfaces, the following analysis, using principles of fluid mechanics, was made by the author.

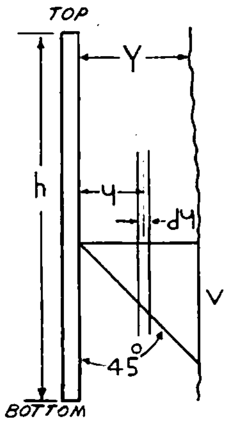


FIGURE 2
WATER FLOWING DOWN A VERTICAL SURFACE

Consider a vertical plane with a layer of fluid moving down one face (figure 2): if the attraction between the plane and the water is strong enough, there will be zero velocity in at least the first layer of molecules. If this attractive force is made stronger, more than one layer of molecules will be immobilized relative to the plane. At some point, however, this attractive force will be reduced enough by space to allow gravity to accelerate the water molecules downward. At some distance away from the plane the attractive force becomes negligible; at which distance, the only force opposing the gravitational pull is the force caused by vicosity of the fluid.

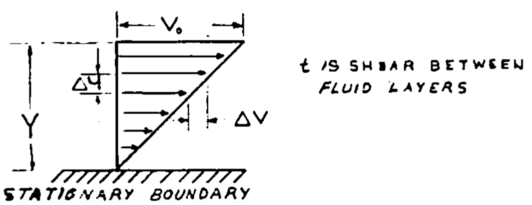


FIGURE 3
THE DEFORMATION OF A FLUID PASSING PARALLEL TO A STATIONARY BOUNDARY

The deformation of a fluid passing parallel to and over a stationary plane boundary is shown in figure 3. According to Rouse (2), shear between layers of fluid can be described by the relation: $S = \frac{dv}{dy}$.

For the situation described, if the flow is laminar and the velocity distribution is a straight line then: $S = m \frac{V}{Y}$

Where S is shear per unit area, m is viscosity, V is maximum velocity, and Y is the thickness of the fluid layer. The total force on the plane in figure 2 is then: $F = ShC = m \frac{V}{Y} hC$ (1)

Where h is the height of the board, C is the width in contact with the water and F is the total force.

If there is no acceleration of the fluid on the plane and if the layer of stationary water is of negligible thickness, the force on the plane is also: $F = hCYP$ (2)

Where P is the density of the fluid. Equating (1) and (2): $m \frac{V}{Y} C = CYP$.

Simplifying: $Y^2 = \frac{mV}{P}$ (3)

Quantity of water moved.

If the plane is moved continuously upward out of a reservoir, water will be moved upward.

It appears that the velocity of the outer layer of fluid will be exactly equal to the upward velocity of the plane but in the opposite direction; that is, the outer layer is stationary with respect to the pool and the inner layer is moving upward with velocity V. If this hypothesis is true, then the weight of water moved is: $Q = C \frac{V}{2} YtP$ (4)

Where t is time. Solving for Y in equation (3) and substituting into equation (4):

$$Q = CPt \frac{V}{2} \left(\frac{Vm}{P}\right)^{1/2} \quad (5)$$

Energy Relationships.

In the analysis of energy relationships, the same assumptions are made as those used above. Additional assumptions made are that there are no losses below the surface of the pool and that no water is accelerated that is not carried upward with the plane.

The energy involved then includes (1) work done in lifting the fluid, (2) fluid friction on the plane caused by the velocity gradient, and (3) the work done in accelerating the fluid. Work in lifting the fluid is Qh and likewise the friction losses are Qh. The first statement comes from the concept of work. The second can be seen to be true from the fact that velocity relative to the pool surface varies from zero to a maximum in a linear manner. If the velocity upward were constant, the quantity of water moved would be proportional to V instead of $\frac{V}{2}$. Since it is proportional to

$\frac{V}{2}$, one-half of the energy is lost as fluid friction. The work done in accelerating the fluid might appear to be $\frac{QV^2}{2g}$; however, since the velocity varies with thickness of the layer, this is not true.

The weight of a small strip of water extending the width of the plane which is moved upward in a given time, t, may be represented by: dw=CPtvdy

Also: $v = \frac{V}{Y} y$

Then velocity energy of the differential quantity is:

$$dE = \frac{dW}{2g} (V)^2$$

Substituting: $dE = \frac{t\,C\,P\,V^3}{2g\;Y^3} y^3 dy$

intergrating this between o and Y gives:

$$E = \frac{C\,P\,V^3\,Y\,t}{8\;g} .$$

Substituting equation (4) in this gives: $E = \frac{QV^2}{4g}$

Efficiency is given by the expression:

$$e = \frac{Qh}{2Qh + \frac{QV^2}{4g}} = \frac{h}{2h + \frac{V^2}{4g}} \qquad (6)$$

From this equation it appears that the efficiency will always be less than 50 per cent.

PROCEDURE

The construction of the apparatus used is illustrated in figure 1. It consisted of a 6" diameter pulley in a suitable enclosure and a 5" diameter pulley which was submerged in the water in the barrel. These two pulleys were connected by the pumping rope. The upper pulley was driven by a ¼ horsepower electric motor through step pulleys and a jack-shaft. The step pulleys were used to obtain different rope speeds.

The water laden rope entered the rear hole in the pump housing, and water was discharged from the front of the pump into a plastic discharge hose. The return hole for the rope was just in front of the entry hole for the rope. For the first test the pump was raised 30 feet beside a silo. The rope being tested was threaded through the pump, down through the barrel, and the two ends were connected by the use of a copper tube. This piece of copper tube was only about 1" long. The speed of the rope was determined by counting the number of times the piece of copper tube went through the pulley in a given period of time. The length of the rope was known; therefore, it was a simple matter to calculate the speed. The approximate speeds used were 8 feet per second, 14 feet per second, and 25 feet per second. The ropes used were 12/16-inch perimeter nylon rope, 16/16-inch perimeter sisal rope, 10/16-inch perimeter solid polyethylene rope, 13/16-inch perimeter twisted polyethylene rope, 10/16-inch perimeter cotton window sash, 7/16-inch perimeter cotton cord, and 7/32-inch perimeter of cotton cord. After testing these ropes at 30 feet, the pump was moved down at 5-feet intervals and all tests were run again. The different heights used were 30 feet, 25 feet, 20 feet, 15 feet, and 10 feet. The amount of water pumped at any given speed and at any given height was measured by allowing water to discharge into a container for one minute and then weighing the container and its contents.

Water temperature was measured and recorded. Viscosity was determined by consulting viscosity-temperature tables. Power to the motor was measured with a wattmeter for each run. After all tests were completed, horsepower delivered to the rope was measured by wrapping a string around the pulley and measuring the pull on the string. The pulley speed was measured with a tachometer. Power input to the motor was measured with the wattmeter as it was during the experiments. A curve of motor input power vs power delivered to the pulley was plotted.

ANALYSIS OF RESULTS

Observations. Several unexpected effects were observed during the experiments. One of these was that tension on the rope affected the quantity of water thrown off the rope. When the rope was under considerable tension, less water was thrown off as the rope moved upward than there was when the rope was loose. At the slower speeds, front hole losses were high; that is, a large quantity of the water was carried around the pulley and out at the front rope hole. At higher speeds, this effect was negligible. Most of the water was discharged out of the discharge opening at higher speeds. The small diameter strings seemed to shake off a larger percentage of the water than larger diameter ropes. The probable cause was that the large diameter ropes were stiffer; therefore, there was less vibration to throw the water off.

No controlled observations were made on submergence effect. However, it was observed that unless the lower pulley was submerged to a certain depth, the discharge would be reduced. In the tests conducted, 6" appeared to be enough submergence to prevent any reduction in flow.

It was thought during the derivation of the formulas that the water would flow smoothly down the rope and that there would be no turbulence on the rope above the water surface in the tank. This proved not to be true. At the lower speeds, flow was approximately laminar. Nodules of water did form on the rope but they moved vertically upward at a speed slower than the rope. However, at the high speeds, the water seemed to be turbulent as it moved up with the rope into the pump.

The copper connector seemed to have some effect on discharge, particularly for some of the ropes. When the connecter went through the pulley it caused the rope to shake and some of the water was lost from vibration.

Inside the pump housing it appeared that water was discharged from the rope in a vertical direction. A piece of sheet metal bent into a smooth curve was placed inside the pump to change the direction of the water 90 degrees.

The shape of the water surface in the barrel during pumping is shown in figure 1. The thickness of the water layer on the rope appeared to be constant after a very short distance above the barrel.

The demonstration referred to earlier and used at engineers day was set up out-of-doors and the wind blew the water off the rope. The rope pump can not be used in an exposed location without shielding it from the wind.

Quantity of Water Discharged. The amounts of water pumped in one minute for the various ropes at the different heights and speeds were recorded. The discharge predicted for one minute was calculated with the formula derived earlier. The quantity measured was always greater than the amount predicted by the equation as is shown in table I.

TABLE I

The ratios of Q measured, to Q predicted are for the two highest speeds at all lifts

Rope	Q Measured / Q Predicted	95 Percent Confidence Interval
Smooth polyethylene	1.2	.2
Twisted polyethylene	1.4	.2
Window sash cord	2.2	.6
Large cotton cord	2.2	.2
Small cotton cord	1.5	.4
Sisal	5.3	.6
Twisted nylon	2.2	.4

These ratios are means for the two higher speeds at all heights at which the ropes were tested. The lowest speed was omitted because it was observed that a large percentage of the water lifted came back down through the front rope hole.

If the equation were correct, the ratios shown in Table I would be unity. It appears that the hypothesized velocity distribution on the rope may be wrong. Perhaps there is an appreciable layer of water on the rope that is immobile. If this hypothesis is correct the proposed equation can be corrected by multiplying by a constant ,k, that is proportional to the immobile layer thickness. The equation would then be:

$$Q = kCPt \frac{V}{2} \left(\frac{Vm}{P}\right)^{1/2} \quad (5a).$$

The constants that should be used are the ratios given in Table I.

Effect of Material. It appears that polyethylene is least desirable for producing maximum discharge. Cotton and nylon appear to be about equal. Sisal is best of all. This large discharge probably was caused by the many fibers projecting outward from the surface of the sisal rope. This characteristic probably caused a thicker layer of water to be immobile with respect to the rope.

Effect of Rope Size. It appears reasonable to assume that as rope diameter decreases the discharge would decrease even faster. This would be caused by increased shearing forces per unit area on the face of the rope. The shearing forces are caused by gravity acting on the water. Some evidence is provided to support this statement by the two cotton cords. These cords had the same type surface configuration, one was 7/32 inches in diameter while the other was 7/16 inches in diameter. As would be expected from the above hypothesis the larger cord had a larger discharge co-efficient.

Surface Configuration. The results from the polyethylene ropes seem to indicate that a twisted configuration gave a slightly higher discharge coefficient than a smooth one. Since the confidence intervals for the coefficients overlap considerably, this conclusion should be regarded as tentative.

Effect of Height of Lift. The rate of discharge did not seem to be affected by height of lift. The discharges at 30 feet for the smooth polyethylene rope, sisal rope, window sash and large cotton cord at the two higher speeds were compared to the discharges of the same ropes at the same speed at 10 feet. The average for 30 feet was 17.4 pounds per minute and for 10 feet it was 16.6 pounds per minute. The difference between these two was not statistically significant.

Energy Considerations. Pump efficiencies ranged from less than 1 percent to 29 percent. Efficiencies decreased as height of lift decreased. This was probably caused by the fact that the energy lost from turbulent flow in the barrel was constant for all heights of lift. Depth of submergence of the lower pulley probably had an effect on losses but no data were recorded to test this hypothesis.

According to the expression derived earlier in the paper, efficiency could never reach 50%. The losses caused by turbulence in the barrel were not considered in this expression, and had they been, the predicted efficiencies would have been even lower. The same assumptions were used in arriving at the efficiency expression as were used in finding the expression for discharge. The measured discharges were higher than predicted discharges. It appears that the factors causing discharge to increase might also improve efficiency.

Efficiency was generally high when discharge was high. It was calculated by dividing water-horsepower by horsepower imput to the pump pulley. Table II gives some data on efficiency.

Rope Inside a Small Pipe. When the pump was 10 feet above the water surface, window sash cord was placed inside a ½-inch diameter steel pipe. In this test discharge was 70 pounds of water per minute. Rope velocity was 24 feet/sec. This compared to a discharge of 18.6 pounds/minute without the pipe.

TABLE II

Efficiency of the Rope Pump at Various Heights Speeds and Materials

Efficiency in Percent	Q Measured No./min. Lbs.	ht ft	Velocity ft/sec
Material: Smooth Polyethylene			
7.2	12.4	25.6	30
3.8	3.4	13.6	30
7.0	12.8	26.0	25
3.1	3.5	13.6	25
1.4	2.3	13.0	30
1.8	8.0	22.2	15
0.8	2.0	12.7	15
1.0	7.2	25.1	10
0.3	1.3	12.9	10
Material: Window sash cord			
9	13.5	26.6	30
10	8.5	14.4	30
7	7.1	14.4	25
5	9.1	12.8	20
2	7.2	24.0	15
3	7.8	13.5	15
2	18.2	26.6	10
3	11.8	14.5	10
Material: Sisal			
24	56.0	24.8	30
29	27.7	13.7	30
24	62.0	23.6	25
21	29.0	13.5	20
12	23.0	13.0	20
6	39.0	20.0	15
10	28.0	13.1	15
5	54.0	22.0	10
7	25.9	12.5	10

SUMMARY AND CONCLUSIONS

The purpose of the study reported here was to determine the effectiveness and efficiency of the rope pump. The essential aparatus consisted of a driven upper pulley inside a housing to facilitate discharge and a lower pulley submerged in water. These were connected by the pumping rope. Tests were run at several heights. Height did not appear to affect rate of pumping. Variables that did affect discharge rate were rope material, perimeter, *velocity*, fluid viscosity, and unit weight of the fluid. The equation proposed to combine these variables is:

$$Q = KCPt \frac{V}{2} \left(\frac{Vm}{P}\right)^{1/2}.$$

The maximum discharge observed was 62 pounds of water per minute for a one-inch perimeter sisal rope. Pump efficiency was 24 percent and rope velocity 23.6 feet per second at this discharge. In another experiment ,not directly connected with the main series, a window sash cord placed inside a ½-inch diameter pipe gave a discharge of 70 pounds per minute. When the cord was not inside the pipe, the discharge rate was 18.6 pounds per minute.

It appears that some form of the rope pump may have practical applications because of its low cost and ease of manufacture.

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IN THE CONVENTION ISSUE

A newsletter has gone out to the members of NACTA asking that material for the February issue be in the hands of the editor by January 15, 1962.

Articles Included:

Program for the 1962 Conference

Preliminary Report on Cross-Country Tour Agriculture-teaching-schools by Mr. Elgin Hall, Orange Coast College.

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Plan to attend the 1962 Conference in Fresno.

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Scientific articles of lasting interest will be considered for publication in the NACTA Journal.

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