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Modeling Autonomous Pumping Machine for Domestic use

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Abstract

The major problems facing the pumping machine users are how to estimate energy in form of power to drive that machine and also the effect of pressure drop change in radius of pipe and the length of total head of pipe that is used in the distribution of fluid from the machine especially the pumping machines that are very useful to day to day activities of human. The aim of this paper is to determine the effect of pressure dropping and the rate of energy consumption in horse power, to determine the effect of radius changes in power consumption rate of the pumping machine and also to know the effect of total head length of pipe in power consumption rate. The mathematical modelling formulation was based on horse power equation of fluid and modified Heigen equation which were used in programming with C# programming language. The result clearly shows that the pressure drop and power consumption rate has greater effect in pumping distribution pattern which is demonstrated in 1 and 2 dimension format. In conclusion this research will definitely assist the designer of water distribution to economically customize the type of pipe, type of machine that will make the pumping rate very efficient with little energy consumption

Keywords: Power, Performances, Evaluation, Pumping machines.

1. Introduction

Water Pumps come in a variety of sizes for a wide range of applications. They can be classified according to their basic operating principle as dynamic or displacement pumps. Dynamic pumps can be sub-classified as centrifugal and special effect pumps. Displacement pumps can be sub-classified as rotary or reciprocating pumps.

In principle, any liquid can be handled by any of the pump designs. Where different pump designs could be used, the centrifugal pump is generally the most economical followed by rotary and reciprocating pumps. Although, positive displacement pumps are generally more efficient than centrifugal pumps, the benefit of higher efficiency tends to be offset by increased maintenance costs.

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Globally, centrifugal pumps account for the majority of electricity used by pumps, the focus of this study is on power consumption rate compare with the discharge rate of water pump. Energy is a very scarce commodity particularly in developing and underdeveloped countries (Anonymous, 2008).

Cost of energy is spirally increasing day-by-day. Generally pumping installations consume huge amount of energy wherein proportion of energy cost can be as high as 40 to 70% of overall cost of operation and maintenance of water works (Anonymous, 2008). Need for conservation of energy, therefore cannot be over emphasized. All possible steps need to be identified and adopted to conserve energy and reduce energy cost so that water tariff can be kept as low as possible and gap between high cost of production of water and price affordable by consumers can be reduced (Akella *et al*., 2007). Conservation of energy is also important and necessary in national interest as the nation is energy deficit due to which problems of low voltage, load shedding and premature failures of equipment are encountered. Some adverse scenarios in energy aspects as follows are quite common in pumping (Ammar, 2011).

Some basic concepts:

Pressure

Pressure is a commonly used term, but it does have a special meaning in hydraulics. It describes the force exerted by water on each square meter of some object submerged in water. It may be the bottom of a tank, the side of a dam, or a pipeline (Hiremath *et al*., 2007). Pressure is normally measured in kilonewtons per square meter (kN/m^2). An alternative to this in irrigation is the 'bar', where 1 bar is equal to100 kN/m^2. Pressure is calculated by:

Thus pressure is force per unit area

Pressure (kN/m^2) =force (kN) / area (m^2)

Pressure measurement

Pressure in pipes can be measured using a *bourdon gauge*. Inside the gauge is a curved tube of oval section, which tries to straighten out when the system is under pressure. The tube is linked to a pointer which moves across a graduated scale and indicates pressure. Irrigators normally measure pressure in the field using these gauges as they are robust and simple to use. Gad (2009) explained that engineers often refer to pressure as a *head of water* in meters (m) rather than a pressure in kN/m^2. If the bourdon gauge was replaced with a long vertical tube, the water pressure in the pipe would cause water to rise up the tube. The height of this water column is a measure of the pressure in the pipe. For example, a pressure of 3 bar in the pipe would result in water rising to a height of 30 m in the tube. Thus, engineers may refer to the pressure as 3 bar or 30 m head of water.

Discharge

The speed at which water flows in a pipe or channel is called the *velocity* and is measured in metres per second (m/s). The *discharge* is the volume of water flowing along the pipe or channel each second, and is measured in cubic metres per second (m^3/s). To understand this, consider the case of water flowing in a 100 mm diameter pipe at a velocity of 1.5 m/s (Akella *et al*., 2007). In one second the quantity of water moving past some point in the pipe will be equal to the shaded volume shown. This volume is numerically equal to the water velocity multiplied by the cross-sectional area of the pipe, i.e., $1.5 \times 0.008 = 0.012$ m^3/s.

Atmospheric pressure

Atmospheric pressure is the pressure of the atmosphere around us, pressing down on our bodies and the surface of the earth. Although air seems very light, when there is a large depth, as at the earth's surface, it creates a pressure of approximately 100 kN/m^2. This is equivalent to l bar or 10 m head of water.

Atmospheric pressure = 100 kN/m^2 = 1 bar = 10 m head of water

In general terms:

Discharge (m^3/s) = cross-sectional area of pipe (m^2) x velocity of water (m/s)

Discharge measurement

Discharge in a pipeline can be measured using a flow meter. The meter indicates the volume of water passing through the pipeline. By noting the time for a given volume of water to pass the discharge can be determined using the formula:

Discharge (m^3/s) = volume of water (m^3) / time (s)

A simple way of measuring discharge from a pipe or sprinkler is to catch the flow in a bucket of known volume, measuring how long it takes to fill. Discharge in open channels can be measured using a weir or flume measuring structure (Ammar, 2011).

Power

Power is often confused with the term energy. They are related, but they have different meanings.

Energy is the capacity to do useful work whereas power is the rate at which the energy is used.

Water energy (kWh) = volume of water (m3) x head (m)

Efficiency

When water pumping machine is not enough just to meet the water power and energy, additional energy and power must be provided because losses occur in transferring fuel energy to water energy via the power unit and pump. The losses in the system are caused by friction and water turbulence and are usually expressed as *efficiency*. This can be expressed both in terms of energy and power use.

Energy use efficiency

This provides an overall indication of the way energy is being used. It would usually be assessed on a seasonal or annual basis.

Power use efficiency

This provides an assessment of the efficiency with which power is converted from the fuel to the water, but only at the moment of measurement. The efficiency may vary over time, particularly if there is wear in the engine and pump. Betka and Moussi (2003) analysed that a system with no friction would have an efficiency of 100% and all the energy and power input would be transferred to the water. However, this is not the case in real life and there are always friction losses in all the components of the power unit and pump. This can result in excessive energy use and high pumping costs. This is an important aspect of pumping and is discussed more fully in the materials and method.

For the purposes of this work, the efficiencies of energy and power use are assumed to be the same. In practice this may not be the case. A seasonal assessment of energy use efficiency may not always give the same value as power use efficiency measured only once or twice during the season. Note that, in calculations using efficiencies, we always use the decimal form [(efficiency in %) / 100] of the value.

Pumping plant efficiency (%) = (water energy / actual energy) x 100

Pumping plant power efficiency (%) = (water power / power input) x 100

Review of design principles of existing Pumping Machine

According to online source, Pumps can be classified by their method of displacement into positive displacement pumps, impulse pumps, velocity pumps, gravity pumps, steam pumps and valueless pumps. There are two basic types of pumps: positive displacement and centrifugal. Although axial-flow pumps are frequently classified as a separate type, they have essentially the same operating principles as centrifugal pumps (Krutzsch, 1986; Khurmi and Gupta, 2005; Norton, 2000; Mallick and Vasudevan, 2010; Mehmood, 2010).

A positive displacement pump makes a fluid move by trapping a fixed amount and forcing (displacing) that trapped volume into the discharge pipe. Some positive displacement pumps use an expanding cavity on the suction side and a decreasing cavity on the discharge side. Liquid flows into the pump as the cavity on the suction side expands and the liquid flows out of the discharge as the cavity collapses. The volume is constant through each cycle of operation (Hill, 1996).

Positive Displacement Pump Behaviour and Safety

Positive displacement pumps, unlike centrifugal or roto-dynamic pumps, theoretically can produce the same flow at a given speed (RPM) no matter what the discharge pressure. Thus, positive displacement pumps are *constant flow machines*. However, a slight increase in internal leakage as the pressure increases prevents a truly constant flow rate. A positive displacement pump must not operate against a closed valve on the discharge side of the pump, because it has no shutoff head like centrifugal pumps. A positive displacement pump operating against a closed discharge valve continues to produce flow and the pressure in the discharge line increases until the line bursts, the pump is severely damaged, or both.

A relief or safety valve on the discharge side of the positive displacement pump is therefore necessary. The relief valve can be internal or external. The pump manufacturer normally has the option to supply internal relief or safety valves. The internal valve is usually only used as a safety precaution. An external relief valve in the discharge line, with a return line back to the suction line or supply tank provides increased safety.

Positive displacement types

A positive displacement pump as analysed by Karassik (2007) can be further classified according to the mechanism used to move the fluid:

i. Rotary-type positive displacement: internal gear, screw, shuttle block, flexible vane or sliding vane, circumferential piston, flexible impeller, helical twisted roots (e.g. the Wendelkolben pump) or liquid ring vacuum pumps.

ii. Reciprocating-type positive displacement: piston or diaphragm pumps.

iii. Linear-type positive displacement: rope pumps and chain pumps.

Rotary positive displacement pumps

These pumps move fluid using a rotating mechanism that creates a vacuum that captures and draws in the liquid

Advantages: Rotary pumps are very efficient because they naturally remove air from the lines, eliminating the need to bleed the air from the lines manually.

Rotary positive displacement pumps fall into three main types:
i. Gear pumps - a simple type of rotary pump where the liquid is pushed between two gears.
ii. Screw pumps - the shape of the internals of this pump is usually two screws turning against each other to pump the liquid.
iii. Rotary vane pumps - similar to scroll compressors, these have a cylindrical rotor encased in a similarly shaped housing. As the rotor orbits, the vanes trap fluid between the rotor and the casing, drawing the fluid through the pump.

Rotodynamic pumps (or dynamic pumps) belong to a category of velocity pump in which kinetic energy is added to the fluid by increasing the flow velocity. This increase in energy is converted to a gain in potential energy (pressure) when the velocity is reduced prior to or as the flow exits the pump into the discharge pipe. This conversion of kinetic energy to pressure is explained by the *First law of thermodynamics*, or more specifically by *Bernoulli's principle*. Dynamic pumps can be further subdivided according to the means in which the velocity gain is achieved (Olukunle, 2006).

These types of pumps have a number of advantages:

i. Continuous energy.
ii. Conversion of added energy to increase in kinetic energy (increase in velocity).
iii. Conversion of increased velocity (kinetic energy) to an increase in pressure head.

A practical difference between dynamic and positive displacement pumps is how they operate under closed valve conditions. Positive displacement pumps physically displace fluid, so closing a valve downstream of a positive displacement pump produces a continual pressure build up that can cause mechanical failure of pipeline or pump. Dynamic pumps differ in that they can be safely operated under closed valve conditions (for short periods of time).

Radial-flow pumps

These are also referred to as *centripetal design* pumps. The fluid enters along the axis or centre, is accelerated by the impeller and exits at right angles to the shaft (radially). Radial-flow pumps operate at higher pressures and lower flow rates than axial- and mixed-flow pumps.

Axial-flow pumps

Main article: Axial-flow pump

These are also referred to as all fluid pumps, the fluid is pushed outward or inward and move fluid axially. They operate at much lower pressures and higher flow rates than radial-flow (centripetal) pumps.

Mixed-flow pumps

Mixed-flow pumps function as a compromise between radial and axial-flow pumps. The fluid experiences both radial acceleration and lift and exits the impeller somewhere between 0 and 90 degrees from the axial direction. As a consequence mixed-flow pumps operate at higher pressures than axial-flow pumps while delivering higher discharges than radial-flow pumps. The exit angle of the flow dictates the pressure head-discharge characteristic in relation to radial and mixed-flow.

Valveless pumps

Valveless pumping assists in fluid transport in various biomedical and engineering systems. In a valveless pumping system, no valves (or physical occlusions) are present to regulate the flow direction. The fluid pumping efficiency of a valveless system, however, is not necessarily lower than that having valves. In fact, many fluid-dynamical systems in nature and engineering more or less rely upon valveless pumping to transport the working fluids therein. For instance, blood circulation in the cardiovascular system is maintained to some extent even when the heart's valves fail. Meanwhile, the embryonic vertebrate heart begins pumping blood long before the development of discernible chambers and valves. In microfluidics, valveless impedance pumps have been fabricated, and are expected to be particularly suitable for handling sensitive biofluids. Ink jet printers operating on the Piezoelectric transducer principle also use valveless pumping. The pump chamber is emptied through the printing jet due to reduced flow impedance in that direction and refilled by capillary action (Olukunle, 2006)

The disadvantages of the commonly used pumping machines

They did not take into consideration the power changes in related to the performance of the machines. The effect of the pressure does not put into consideration, which is fluctuation in the pressure at which the machine is working. Based on these disadvantages, there is need for proper design of autonomous pumping machines that can take care of the afore-mentioned deficiency.

Fluid is defined as a substance, which cannot withstand a shear force or stress without moving when compared with solid (John and Williams, 2009). Fluid can also be defined as a substance which continuously deform when a force is applied (Raisinghania, 2003). John and Williams (2009) further classified fluid as liquids or gases. A liquid has intermolecular forces which hold it together so that it possesses volume but no definite shape while gas consist of intermolecules in motion which collide with each other tending to disperse it so that a gas has no set volume or shape. They also classified fluid by the types of their flow into laminar and turbulent flow.

John and Williams (2009) classified fluid by the types of their flow and this may be laminar or turbulent flow. The term laminar flow means a fluid flow which flows in laminas or layers, it can also be describe as a type of fluid flow in which the fluid travels smoothly or in regular paths or a fluid flow in which individual particles of the fluid follow paths which do not cross those of the neighbouring particles. Laminar flow is not normally found except in neighbourhood of a solid boundary (Massey, 2006) while the turbulent flow is one for which the velocity component have random turbulent fluctuations imposed upon their mean values. Massey (2006), further discuss that turbulent flow are the type in which individual particles of fluid are no longer everywhere straight but are sinuous.

2. Materials and Methods

The work done by any machine can easily be related to force and distance and when we are talking about force we also need to refer to power at which the force is acting and the work done by that machine. The main concern of this study is to measure the average power of a simple machine in related to the force which a particular machine can do a work especially the pumping machine that needs a particular to inject fluid through the pipe and in that case, a particular power is being performed before the work can be done at a particular time.

The power is the time rate at which the work is done by machine according to Okeke *et al*., (2008).

The mathematical formulae were developed with three assumptions:

1. Power is measure in Watt.
2. Flow is taking place in a pipe at a particular temperature.
3. The pressure rate of fluid is based in bar measurement.
4. The diameter of the pipe is measured in meter.

The model will base on equation Power measured in Horse Power as follow:

$$WP = \frac{Qh}{3960}, \qquad (1)$$

where WP is power (Horse Power).

Equation (1) is equation of fluid to determine the power of machine to drive the fluid in horse power:

Q is discharge rate $\frac{m^2}{s}$, *h* is total head of pipe (m).

From equation (1)

$$Q = V.A_1, \qquad (2)$$

where V is velocity rate ($^{m}/_{s}$). A_1 is the surface area of the pipe Velocity from equation (2) can be determined from Heagen postulates given as (Raisinghania, 2003):

$$V = \frac{Pr^2}{4K} + A_2 \log_e r + B. \quad (3)$$

To develop the model, the assumptions are:

1. Velocity is taken place at different temperature.
2. Flow of fluid is taken place inside pipe.
3. Effect of pressure drop, change in radius of pipe, and change in total head of pipe are considered to determine the Power.
4. Power of machine is determine in horse power rating.

From equation (3)

$$V = \frac{Pr^2}{4K} + A_2 \log_e r + B.$$

Taking the boundary condition as 0<e<r:

when V=0 and A_2 = 0, when boundary condition, we have:

$$B = \frac{-Pe^2}{4K}. \quad (4)$$

Putting equation (4) into equation (3) gives:

$$V = \frac{-Pe^2}{4K}\left(1 - \frac{r^2}{e^2}\right) \quad (5)$$

and putting equation (5) into equation (1)

$$W_p = \frac{\frac{-Pe^2}{4K}\left(1-\frac{r^2}{e^2}\right)\pi e^2.h}{3960} \quad (6)$$

Also from equation (3), when boundary conditions taken are A=0 at V=0, then

$$R_3 = \frac{-Pe^2}{4K}$$

and with this, we have:

$$W = \frac{\frac{-Pe^2}{4K}.h}{3960},$$

where V is Velocity (m/s), P is Pressure (bar), r is the radius of the pipe (m), K is dynamic viscosity (m^{-2}/s).

To determine the power of the pumping machine across the pipe, we have the following equation:

$$W_p = \sum_{e=-r}^{e=r} \frac{\frac{-Pe^2}{4K}\left(1-\frac{r^2}{e^2}\right)\pi e^2.h}{3960}, \quad (7)$$

which clearly show the effect of changing in radius of the pipe in determining the power needed to run a particular pumping machine.

Also, we have the equation below:

$$W_p = \sum_{e=-H}^{e=H} \frac{\frac{-Pe^2}{4K}\left(1-\frac{r^2}{e^2}\right)\pi e^2.h}{3960}, \quad (8)$$

which determines the total head of the pumping machine based on the selected pipe.

3. Results and Discussion

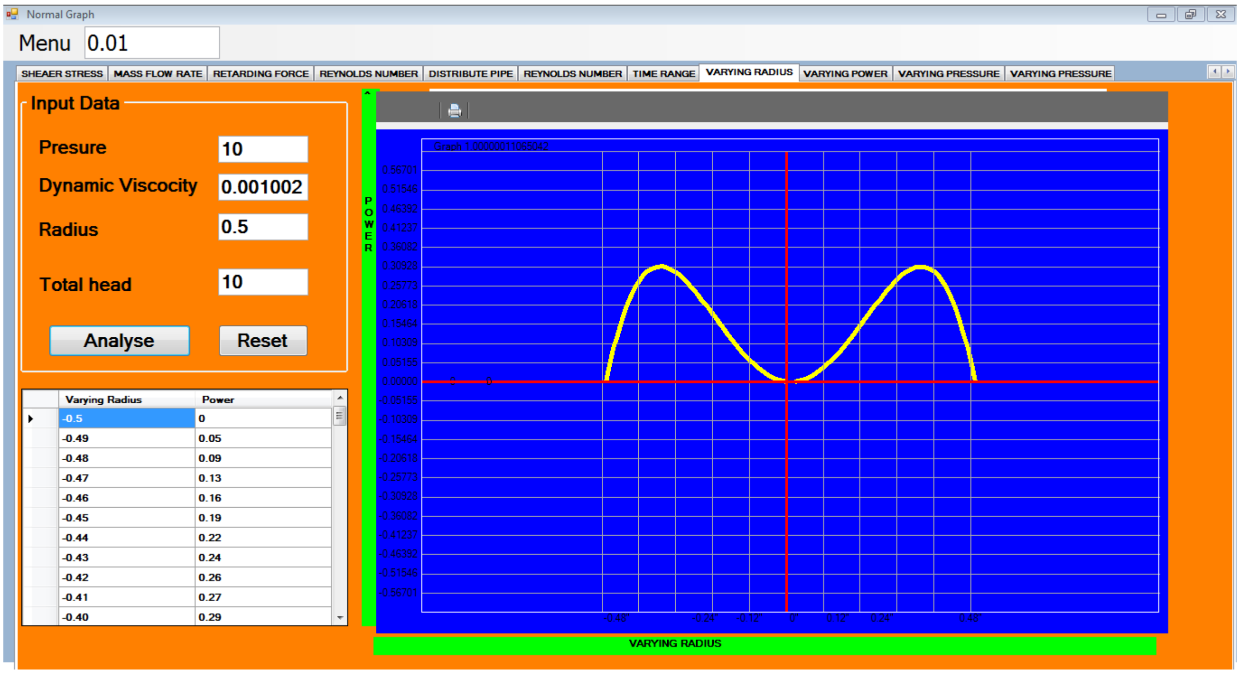

Figure 1: Effect of Changing in radius of the water pipe in determining the power needed to run the pumping machine

From figure above, it can be described that the higher the radius, the more power consumption the machine demands under ideal condition and at a given constant temperature (in which the temperature applies to this is 20°C.

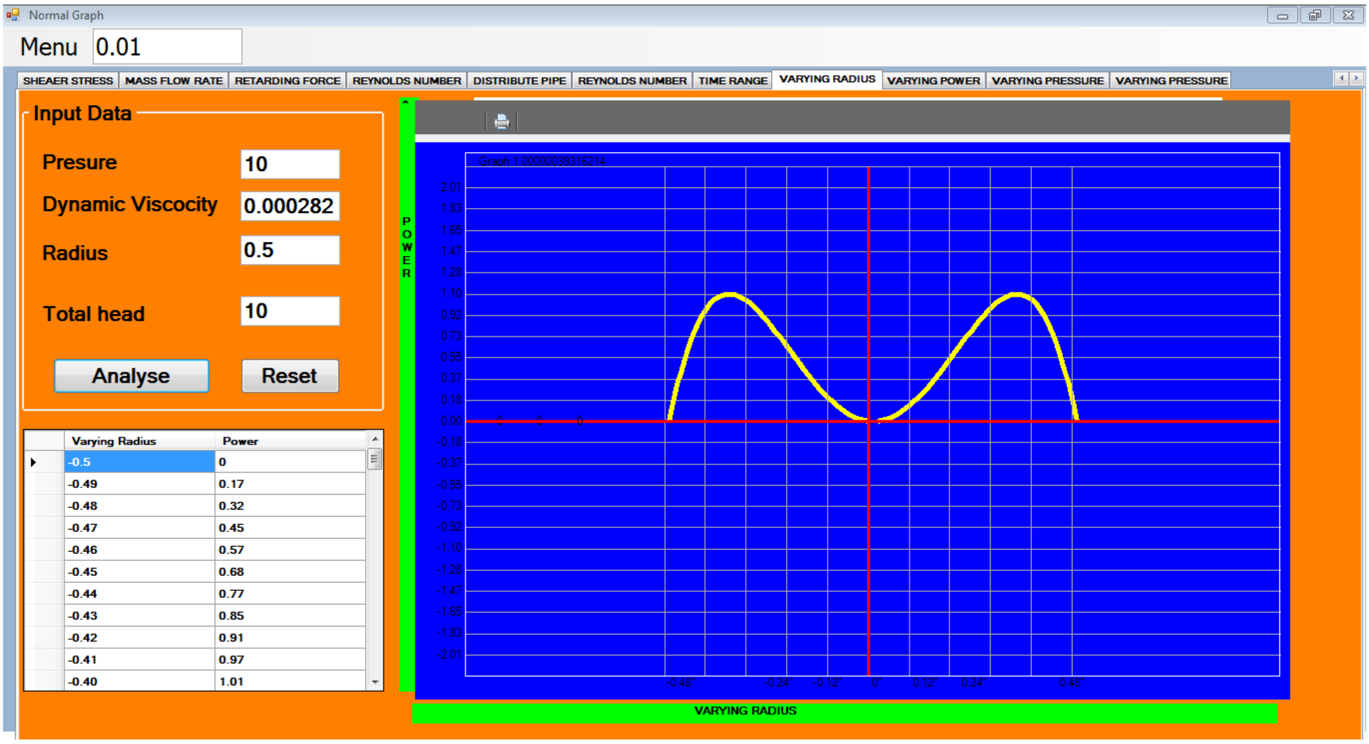

Figure 2: Effect of Changing in radius of the water pipe in determining the power needed to run the pumping machine at a higher temperature

From Figure 2, it can be described that the higher the radius, the more power consumption the machine demands under ideal condition but at a higher temperature it was observed to have the same flow pattern and uniform power consumption (in which the temperature applies to this is 100°C..

Table 1: chart of Changing in radius of the water pipe in determining the power needed to run the pumping machine (at 20°C)

Varying Radius	Power
-0.50	0
-0.49	0.05
-0.48	0.09
-0.47	0.13
-0.46	0.16
-0.45	0.19
-0.44	0.22
-0.43	0.24
-0.42	0.26
-0.41	0.27
-0.40	0.29
-0.39	0.29
-0.38	0.30
-0.37	0.31
-0.36	0.31
-0.35	0.31
-0.34	0.31

-0.33	0.30
-0.32	0.30
-0.31	0.29
-0.30	0.29
-0.29	0.28
-0.28	0.27
-0.27	0.26
-0.26	0.24
-0.25	0.23
-0.24	0.22
-0.23	0.21
-0.22	0.19
-0.21	0.18
-0.20	0.17
-0.19	0.15
-0.18	0.14
-0.17	0.13
-0.16	0.11
-0.15	0.10
-0.14	0.09
-0.13	0.08
-0.12	0.07
-0.11	0.06
-0.10	0.05
-0.09	0.04
-0.08	0.03
-0.07	0.02
-0.06	0.02
-0.05	0.01
-0.04	0.01
-0.03	0.00

Table 2: Charts of Changing in radius of the water pipe in determining the power needed to run the pumping machine at a higher temperature (100ºC)

Varying Radius	Power
-0.50	0
-0.49	0.17
-0.48	0.32
-0.47	0.45
-0.46	0.57
-0.45	0.68
-0.44	0.77
-0.43	0.85
-0.42	0.91
-0.41	0.97
-0.40	1.01
-0.39	1.05
-0.38	1.07
-0.37	1.09
-0.36	1.10
-0.35	1.10
-0.34	1.09
-0.33	1.08
-0.32	1.06
-0.31	1.04
-0.30	1.01

-0.29	0.98
-0.28	0.95
-0.27	0.91
-0.26	0.87
-0.25	0.82
-0.24	0.78
-0.23	0.73
-0.22	0.69
-0.21	0.64
-0.20	0.59
-0.19	0.54
-0.18	0.50
-0.17	0.45
-0.16	0.40
-0.15	0.36
-0.14	0.32
-0.13	0.28
-0.12	0.24
-0.11	0.20
-0.10	0.17
-0.09	0.14
-0.08	0.11
-0.07	0.08
-0.06	0.06
-0.05	0.04
-0.04	0.03
-0.03	0.02
-0.02	0.01
-0.01	0.00
0.00	0

4. Conclusion

Based on our findings, we conclude that any changes in radius of the pipe will automatically have effect in the amount of the power that a particular machine will need to run it and we recommend the following:

1. The temperature will automatically affect the power a particular pumping machine will need to work.
2. The size of the pipe has effect on the power needed to pump water from source to destination.
3. Since the size (i.e. distance and radius of the pipe) determines the power of the pumping machine, hence, autonomous pumping machines can be designed to adopt the varying size and distance in consideration to the power consumption.

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