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MODELING OF PIPE DIAMETER USING VELOCITY METHOD FOR PRESSURIZED FLOW PIPE NETWORK AT HAMELMALO AGRICULTURAL COLLEGE – A CASE STUDY

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Abstract: The network of pipes and valves form an essential and integral part of transmission and deliverance of water in any given agricultural system. The network comprises of a number of interconnected pipes of various dimensions in different shapes and sizes. These pipes are further connected by a number of control valves and other minor fittings depending on the physiographic nature of the system. The design and analysis of pipe network involves the determination of flow rate, pressure drop and diameter of pipe. For any type of pipe network designed for the fluid flow, the pressure head loss along the two different cross sections of pipes and the minor losses owing to the additional components involved in network contribute to the total losses of the flow in the network. The optimum pipe designed for the flow of water involves minimum loss with a reasonable cost throughout the network. The velocity of fluid is a fundamental quantity which characterizes the pressure drop when designing a pipe for a given network. By establishing the limits on the velocity factor a suitable diameter for a pipe can be designed. The optimum diameter modeled using Velocity method is highly effective in hydraulic design.

Keywords: agricultural system, pressure head losses, minor losses, velocity method, optimum diameter

1. INTRODUCTION

The flow of fluid through pipes as medium of propagation is the usual method of transmission and distribution from small to large discharges. The pressure of fluid may be greater or less than the atmospheric pressure during the flow process. The fluid is assumed as an incompressible flow in which the density is assumed constant and the velocity is uniform over each area of the network for any agricultural system. The nature of the network is primarily influenced by the various physical laws and the topological features of the network. When the fluid is transmitted through the pipelines of a network, the Law of conservation of mass assumes the most simplified version between the entrance and exits of each layer of the network resulting in the Continuity equation.

The velocities between the various sections of the network can be related using the Continuity equation. On application of the Newton's second law of motion to the differential form of Continuity equation results in the Bernoulli's equation which forms the basic equation for the flow of fluid through a given pipeline. The design of the pipeline depends on the nature of the fluid flow which depends on the dimensionless number termed as the Reynolds number (Re). This number describes the nature of flow into various zones. It can either be as laminar or turbulent zones or an intermediate between them termed as a transition zone.

The empirical equation relating the pressure head loss due to friction along the pipe sections for the various lengths to the mean velocity of flow of the fluid is termed as the Darcy–Weisbach equation. The friction factor term contained in the equation is called as the Darcy's friction factor [1].

The Colebrook–White formula expresses the friction factor as a function of relative roughness of pipes and Reynolds number. Since it has an implicit version, a direct solution cannot be obtained. Owing to the restrictions in the Colebrook–White equation, several methods of approximations were established by various researchers to overcome the drawbacks in the equation. The initial approximation were proposed in the form of diagrams and the final accepted version of the chart came to be termed as the Moody's diagram which represents the determination of friction coefficient as a function of Re and average roughness of pipes [2]. Various explicit equations were proposed to replace the manual use of charts. Most of the equations proposed had a limited range of Re and hence can be applied only for certain design problems [3]. The empirical equation proposed by Swamee and Jain [4] in 1976, inter relating the diameter of pipe, discharge and pressure head loss enabled the application of Darcy–Weisbach equation because of its accuracy and entire range of application and had replaced the limitations of less accurate empirical equation such as the Hazen– Williams equation. The pipelines generally have a long period of life and less maintenance cost when installed properly. When operated under pressure, these pipeline networks can be applied in uphill or downhill sections, allowing distribution of water which is not accessible to channels or other distribution systems [5]. The initial cost of laying the network is generally high but more economical under field conditions when considered for long term use. The economic pipe diameter designed usually depends on the friction losses of the different pipes based on the rate of flow of water for the chosen velocity [6].

There are head losses which are incurred at pipe bends, junctions, valves and various sudden entrances and exits of the network [1] in addition to the friction losses which occurs due to the roughness of the pipes based on its material of manufacture. These losses are termed as the Minor losses. These losses occur due to the disruption of the flow due to the installation of various fittings mentioned above. For pipeline networks of larger lengths the losses are usually caused by the friction effect and losses incurred by the fittings are minimal. However, in case of shorter pipelines the proportion between major and minor pipelines is considerably high [7]. The effect of the minor losses on water transmission pipelines has been studied in detail by means of a computer programming language by the authors of [8]. Different methods of optimum pipe diameter selection have been proposed by various designers. Various techniques have been recommended by [9]. The techniques adopted are namely the economic method, the unit head loss method, the percent head loss method and the velocity method. These techniques are based on various criteria of pipe selection. [10] has mentioned three techniques for the optimum pipe selection and has concluded the result based on the comparison of the three methods namely the Jack's cube method, the Head loss gradient method and the Smit's method based on friction losses and the cost analysis of the pipes.

There are two approaches based on which the design of the pipeline network is framed. When the pressure head losses are to be determined for the entire network based on the basic fundamental equations of hydraulics, given the diameter and flow rate then such an approach is termed as the Analysis approach. When the various requirements are placed in designing a network of pipeline for a given system in terms of allowable pressure drop and required volume of rate of flow given the fluid properties and material composition of the pipes, a suitable diameter can be designed for the pipeline line system. Such an approach is called as the Design approach [11]. [12] developed two correlation equations describing the pressurized flow in pipes under normal pressure ranges. This method is generally preferable for preliminary sizing of pipes. The classical method of head loss gradient has a requirement of designing the diameter of pipe in such a way that it ensures a specified amount of minimum pressure at some point. The designed diameter solution is usually obtained by a trial and error solution. Four explicit mathematical formulas for determination of friction factor in a pipe flow is given by [13]. The diameter can be derived without an iterative solution using the method described in [13] provided the input quantities are known. The third and most commonly adopted method in designing the diameter of pipes is based on the fluid velocity.

From the literature review it is observed that different methods of design are available for the manufacture of pipes depending on the parameters considered. The design and estimation of the diameter can either be based on analysis or design approach depending on the requirement of the designers. The diameters designed are optimized based on the head loss friction and cost analyses as the major objective function. The pipe sizes designed using each parameter as the major criteria results in a design which can vary with objective functions. Hence pipe sizes designed should be able to meet the optimized objective function as well as the requirement of the designers based on the physiographic nature of the system. In this attempt, Velocity is taken as the major criteria for designing the pipeline network system optimizing the only objective function namely the head loss friction loss as the major criteria so as to design an effective network for the case study considered.

2. MATERIALS AND METHODS

The site location selected for incorporating the case study was Hamelmalo Agricultural College farm which is sub divided into various sub–plots at Hamelmalo Agricultural College (HAC). HAC is located in the semi–arid regions of Eritrea in a geographic location of 15°52'21.23" N latitude and 38°27'41.79" E longitude at an elevation of about 1285 m above mean sea level at 12 km North of Keren along Keren–Nakfa road. It is bordered by River Anseba towards the North and North–West by Shilaket which is a tributary of River Anseba. The total area of the college is about 76.3 hectare. The farm area is estimated to be around 16.3 hectare as shown in Figure1 [14] with an average temperature of 29°C.

Figure 1: Location of Hamelmalo Agricultural College (HAC)

The existing pipeline network at HAC is a linear type network. There are three wells functioning in the farm. One is a hand dug well (well 2) constructed during the period of an Italian investor and the other two are bore–hole wells respectively. One bore well has a yield of 3 l/S (well 3) and the other bore well has a yield of 18 l/S (well 1). The source of water for these wells is from River Anseba which recharges it as per the requirement. The hand dug well has a yield of 8.3 l/S. The network starts from the two wells namely well 1 and well 2 and is allowed to meet a meeting point junction (GV1). This is done in order to ensure that the failure of one well would not allow the crops to face moisture deficit as the other well would act as a redundant. The network in the HAC farm consists of mainline, sub mains, manifolds, gate valves and various emission devices. The compositions of the material in which the pipes are made up of are galvanized iron (G.I.) and poly vinyl chloride (PVC). Few of the pipes are laid above the ground and few of them lie under the ground. The network of pipeline system currently existing at HAC is as shown in Figure 2 [14].

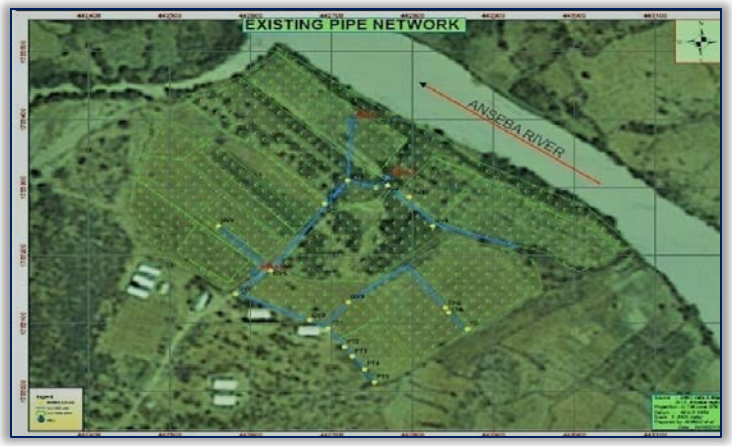

Figure 2: Existing Pipe network at HAC

3. DETERMINATION OF HYDRAULIC PRESSURE LOSSES FOR THE EXISTING PIPE NETWORK AT HAC FARM

The initial step of determination of the diameter for the existing conditions at the farm was the design of the hydraulic analysis chart in order to study about the topographic conditions in detail. The hydraulic analysis chart of the network for the existing conditions at HAC farm is given in Figure 3.

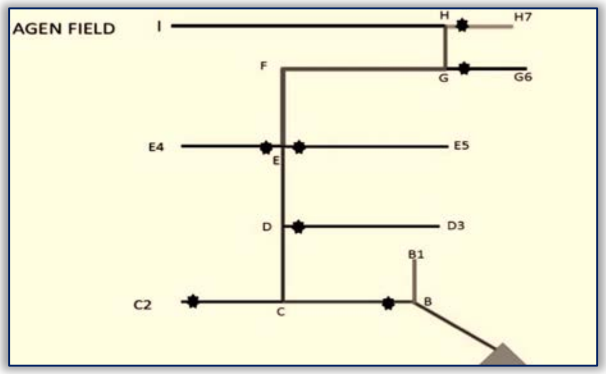

Figure 3: Hydraulic analysis chart of HAC Farm

The Farm's network supply is divided into 15 links for the purpose of irrigation and supplying water to various sub–plots. The supply is divided into two schedules namely schedule 1 and schedule 2. The triangle in Figure: 3 denote the submersible pump of well 1 and is assumed as A for convenience of nomenclature. During schedule 1, the water is transmitted through links AB, B1, BC, C2, CD, D3, DE, E4 and E5 respectively. Followed by schedule 2 in which the water is transmitted through links namely EF, FG, G6, GH, H7 and HI. The various links which are mentioned in the above chart refers to various sub–plots as per the division of departments and research sections functioning in the college. The black operator symbol shown in the chart denotes the gate valves for operation. The systematic hydraulic chart representation with respect to departments for the existing HAC farm is shown in Figure 4.

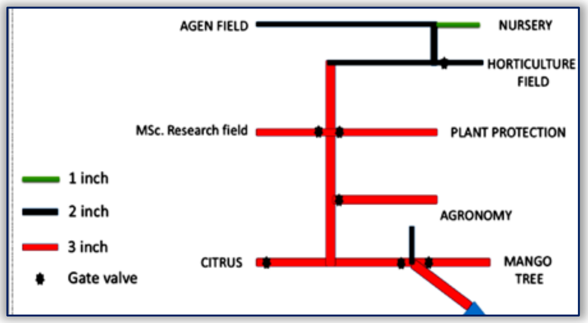

Figure 4: Systematic hydraulic analysis chart of the existing HAC farm with reference to departments

For the determination of various losses related to the transmission of water through the network, the installed pipeline diameter is to be determined. The initial procedure was the determination of the elevation losses of the existing pipe network. While conducting the topographic survey at the farm different instruments were used including the total station, GPS, reflector and a measuring tape. The details were collected for various points involving the shifting of instrument from different point of interests along with the reflector shifted at every interval for the preparation of topographic map. The elevation details of the entire farm at various points of interest were determined in order to estimate the elevation losses available in the existing network during the transmission of water.

The minor or local losses are usually considered insignificant as compared to the major losses. The minor losses arise in the network due to the installed fittings. These installed fittings can be in the form of bends, unions, valves and tees or any other type of fittings involved between the pipelines. The determination of the minor losses is usually a time consuming cumbersome process and hence various rules of thumbs are applied in order to estimate the minor losses of a given network [8]. [15], [8] discusses a method where the minor losses represent 10% of the major friction losses in the network. In this study, since few of the fittings were buried underground, the assumption of the minor losses representing 10% of the major losses was taken into account. The network fitting of a corresponding link is shown in Figure 5. These fittings resulted in the minor loss which added up along with the major loss during the propagation of water through the network resulting in the pressure drop. The minor losses arising in the network at HAC farm were usually related to the fittings such as gate valves, tees, unions, elbows, sudden contractions and enlargements.

Figure 5: Fittings of a network link at HAC Farm

The major pressure losses during the propagation of water through the network can be determined using the two commonly used equations namely the Darcy–Weisbach equation and Hazen–Williams equation [1]. In this study, the Darcy–Weisbach equation was adopted in order to determine the major friction losses due to its advantages over the Hazen–Williams equation. The Hazen–Williams equation is an empirical formula and is much accurate only for turbulent flow range. The temperature of water propagating through the network must be in the range of 40 to 75 °F and the kinematic viscosity of the water is around 1.1 centistokes. Moreover, Hazen–Williams equation is valid only for water flow and not much to other type of fluids. At high temperatures, where the water becomes hot, the estimation of friction loss would result in error [16]. The determination of friction factor 'f' in the Darcy–Weisbach equation can be determined using various empirical equations as suggested by various researchers. The Swamee–Jain's (S–J) equation was used in order to estimate the friction factor of the Darcy–Weisbach equation in this case study. The empirical equation predicted the values of the friction factor and further the total major loss was estimated using the Darcy–Weisbach equation. The S–J equation was proposed in 1976. The friction factor can be estimated for Reynolds number lying between turbulent, transition and laminar zones of the flow in the network. The equation is given by (1)

$$f=0.25\log(\varepsilon/3.7D+5.74/Re^{0.9})^{-2} \quad (1)$$

The value determined by the above formula is further substituted in the Darcy–Weisbach equation and the major friction loss is determined for the various links of the flow network.

4. MODELING OF OPTIMUM PIPE DIAMETER USING VELOCITY METHOD

There are a number of optimum methods by which pipes are modeled based on the application of use. A number of physical parameters can be used in order to design the diameter of the pipe. These physical parameters would act as a constraint depending on its range. Based on the limits of the constraint, the pipe diameter is designed which would optimally fit for the network. [10] has described various methods for optimum pipe designing at HAC Farm based on discharge, pressure gradient and annual pumping hours.

In this case study, an optimum design for the network at HAC was designed based on the physical parameter 'Velocity'. Using the velocity of flow as a constraint medium, the optimum design was designed for the whole network. The limit of velocity for the flow of water at various links was assigned a constant based on the optimum velocity design method. The velocity limit was maintained between a nominal range of 1.5 m/S and 3 m/S [9]. The minimum velocity was assumed as 1.5 m/S and the maximum velocity was assumed as 3 m/S for the design criterion. The theory of the method suggests that the optimum design of the pipe is so designed such that the average velocity V for a given flow rate Q in a circular pipe, the diameter d is given by equation (2) [17]

$$d = \sqrt{\frac{4Q}{V\pi}} \quad (2)$$

In general terms, the optimum diameter designed using the velocity method does not only relates to the friction losses and energy costs but also can be correlated with better heat transfer in case of fluids. The velocity profile of the fluid particles varies depending on the nature of the flow. If in case the flow is a laminar, the profile is said to be a parabolic one whereas, in case of turbulent flow, a flat distribution profile exists. The pipe walls in contact with fluid usually maintain a velocity of zero and it increases as the distance rises from the walls of the pipe with the fluid in propagation [11].

The conveyance and distribution system of water are designed in such a way so as to meet the basic requirements of providing the required flow rate and head. In order to meet the above need, suitable pipe materials are required so as to provide an efficient usage of the network system. A plethora of pipe materials are available for the design purpose based on the requirements. During the last decades, pipes made of polyvinyl chloride (PVC), coated steel pipes, ductile iron pipes, Polyethylene pipes are much into practice [18]. [19] discusses about the features and benefits of PVC in the piping system. Considering the advantages and the features of PVC over the other materials available for the design of the piping system, PVC is assumed for the design criteria for the pipe network at HAC using the velocity method.

3. RESULTS AND DISCUSSION

The length of the existing pipes of the various sub plots was measured. The pipe length was measured using the tape and odometer. The survey of the whole farm was initiated further using theodolite and GPS in order to determine the elevation difference between the farm and the water source. Further, the various bends, elbows, valves and other fittings of the pipeline system was noted. Considering the underground fittings, the 10% of the major loss for the minor losses was considered in order to evaluate the amount of minor losses contribution to the overall loss. The graduated container along with a stop watch was used to determine the flow rate experimentally for the various sub–plots. The thermometer was used in order to determine the temperature of water, as the physical characteristics of water such as viscosity and water varies with temperature. Considering the limitations of Hazen–Williams formula the major friction loss was estimated for the existing pipeline network using the Darcy–Weisbach equation. The estimated value of the losses is listed in Table 1.

The total pressure drop in the pipeline network for the existing diameter of the HAC farm was estimated to be the total sum of the elevation losses, major friction losses and the minor losses which arises due to the various fittings available in the network. These minor losses amount to 10% of the major friction losses. The analysis approach of pipe sizing methodology was adopted for determining the existing diameter of the HAC farm. The pressure losses were determined for the existing system by using the various fundamental flow equations where the diameter of the pipe is known [11]. The various losses determined based on elevation, major pressure drop and minor fitting losses were combined in order to determine the arithmetic sum of the total losses based on Bernoulli's equation. Based on assumptions, the flow through the pipeline is considered as a steady flow with constant density.

Table 1: Determination of the Total losses in the existing pipeline network at HAC Farm

Links	Length (m)	Diameter (m)	Diameter (inch)	Velocity (m/S)	Discharge (m³/S)	Reynolds Number (Re)	Material of Pipe	Elevation Losses (m)	Major Losses (m)	Minor Losses (m)
AB	70	0.0762	3.00	3.946	0.0179	375907.8	G.I.	0	9.76	0.98
BC	42.3	0.0762	3.00	3.362	0.0153	320303.2	G.I.	0.896	4.30	0.43
B1	38	0.0508	2.00	0.986	0.0019	62651.32	PVC	0	0.22	0.02
C2	43.3	0.0762	3.00	0.877	0.0039	83535.1	G.I.	0	0.32	0.03
CD	177.4	0.0762	3.00	2.921	0.013	278304	G.I.	0	13.66	1.37
D3	89.7	0.0762	3.00	0.657	0.0029	62651.25	G.I.	0	0.38	0.04
DE	61.2	0.0762	3.00	2.655	0.0121	252889.8	G.I.	4.594	3.90	0.39
E4	106.2	0.0762	3.00	0.877	0.0039	83535.1	G.I.	0	0.78	0.08
E5	74	0.0762	3.00	0.877	0.0039	83535.1	G.I.	0	0.54	0.05
EF	116.3	0.0762	3.00	2.289	0.0104	218096	G.I.	0	5.54	0.55
FG	53.5	0.0762	3.00	2.15	0.0098	204861.7	G.I.	4.33	2.25	0.23
G6	12	0.0508	2.00	1.479	0.0029	93976.95	G.I.	0	0.18	0.02
GH	73	0.0762	3.00	1.231	0.0056	117262.4	G.I.	0.35	1.03	0.10
H7	33	0.0508	2.00	1.479	0.0029	93976.95	G.I.	0	0.50	0.05
HI	65.5	0.0381	1.50	3.508	0.0039	167070.1	PVC	0.92	3.40	0.34
	TOTAL= 62.53							11.09	46.76	4.68

Table 2: Design of optimized diameter using Minimum Velocity Method for pipeline network at HAC Farm (Assume V=1.5 m/S, Material: PVC)

Links	Length (m)	Diameter (m)	Diameter (inch)	End Discharge (m³/S)	Reynolds Number (Re)	Elevation Losses (m)	Major Losses (m)	Minor Losses (m)	Total Losses (m)
AB	70	0.123	4.86	0.0177	230596.51	0	0.98	0.098	1.078
BC	42.3	0.115	4.54	0.0170	228675.87	0.896	0.60	0.060	1.556
B1	38	0.041	1.62	0.0019	76865.50	0	2.00	0.200	2.200
C2	43.3	0.058	2.29	0.0039	108704.24	0	1.50	0.150	1.65
CD	177.4	0.098	3.86	0.0112	182949.59	0	3.28	0.328	3.608
D3	89.7	0.050	1.98	0.0029	94140.633	0	3.69	0.369	4.059
DE	61.2	0.083	3.29	0.0153	156267.12	4.594	0.89	0.089	5.573
E4	106.2	0.050	1.98	0.0029	94140.63	0	4.38	0.438	4.818
E5	74	0.050	1.98	0.0029	94140.63	0	3.05	0.305	3.355
EF	116.3	0.114	4.49	0.0150	212853.39	0	1.79	0.179	1.969
FG	53.5	0.113	4.45	0.0136	210905.20	4.33	0.83	0.083	5.243
G6	12	0.050	1.98	0.0028	94140.63	0	0.49	0.049	0.539
GH	73	0.095	3.75	0.0104	177723.95	0.35	1.40	0.140	1.890
H7	33	0.050	1.98	0.0028	94140.63	0	1.36	0.136	1.496
HI	65.5	0.058	2.29	0.0037	108704.23	0.92	2.27	0.227	3.417

Table 3: Design of optimized diameter using Maximum Velocity Method for pipeline network at HAC Farm (Assume V=3 m/S, Material: PVC)

Links	Length (m)	Diameter (m)	Diameter (inch)	End Discharge (m³/S)	Reynolds Number (Re)	Elevation Losses (m)	Major Losses (m)	Minor Losses (m)	Total Losses (m)
AB	70	0.087	3.44	0.016	326112.71	0	5.22	0.52	5.75
BC	42.3	0.083	3.29	0.014	312419.56	0.896	3.32	0.33	4.55
B1	38	0.029	1.14	0.001	108704.23	0	10.56	1.05	11.63
C2	43.3	0.041	1.62	0.003	153731.00	0	7.93	0.79	8.73
CD	177.4	0.079	3.12	0.013	295811.21	0	14.86	1.48	16.36
D3	89.7	0.035	1.40	0.002	133134.95	0	19.53	1.95	21.49
DE	61.2	0.075	2.97	0.011	281970.42	4.594	5.43	0.54	10.57
E4	106.2	0.040	1.58	0.003	150350.18	0	19.98	1.99	21.98
E5	74	0.041	1.62	0.003	153731.00	0	13.55	1.35	14.91
EF	116.3	0.069	2.73	0.010	259405.10	0	11.39	1.13	12.54
FG	53.5	0.065	2.58	0.008	245378.56	4.33	5.60	0.56	10.49
G6	12	0.035	1.40	0.002	133134.95	0	2.61	0.26	2.88
GH	73	0.048	1.89	0.004	179378.46	0.35	11.11	1.11	12.58
H7	33	0.035	1.40	0.002	133134.95	0	7.18	0.71	7.91
HI	65.5	0.024	0.97	0.001	92832.40	0.92	22.05	2.20	25.18

Based on the velocity method of design criteria, the design approach of pipe was adopted in order to determine the optimum pipe diameter of the network using the velocity as the major factor. The velocity range of 1.5 m/S and 3 m/S was considered as the minimum and maximum velocity factor for the purpose of design criterion. By a known value of the flow rate, the optimum diameter is calculated from the basic fundamental continuity equation. Table 2 and Table 3 displays the optimum diameter designed using the velocity design criterion method. Figure 2 and Figure 3 represents the total head loss estimated for the existing links using the Velocity method design criterion. The design method adopted uses PVC as the material for the pipeline network, considering its benefits over other materials. PVC materials are generally flexible and inexpensive as compared to other materials.

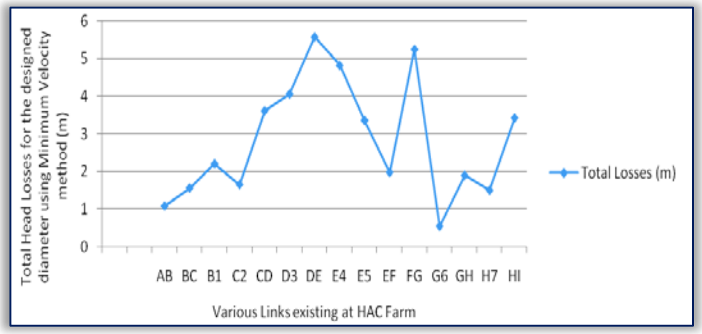

Figure 6: Graphical response of the Total head losses for the designed diameter using Minimum Velocity method for the various links existing at HAC Farm

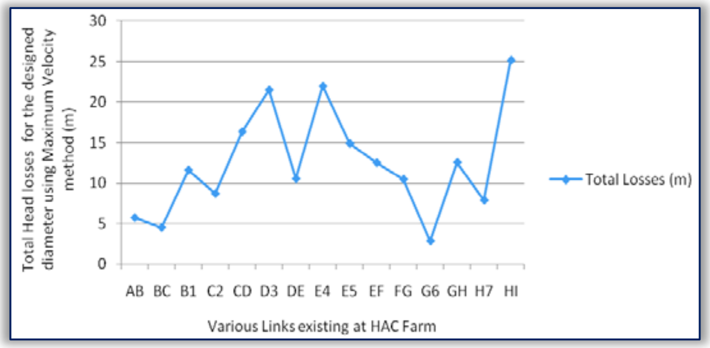

Figure 7: Graphical response of the Total head losses for the designed diameter using Maximum Velocity method for the various links existing at HAC Farm

The results in Table 2 and Table 3 gives detailed analyses of the pipe design designed using the Velocity Method of Pipe design. The velocity of the fluid flow through the pipe, is taken as constrain and the required flow rate is assumed based on the features of the farm. The velocity is assumed constant within a range of 1.5 to 3 m/S, where 1.5 m/S the initial velocity is considered minimum and 3 m/S is considered the maximum velocity of the fluid flow. Based on the basic fundamental Continuity equation, the optimum pipe diameter is designed for the various links considering the over– all head loss as the major objective function in this study.

Based on the results and the graphs, it is analyzed that the diameter designed using the minimum velocity method is much better in performance as compared to the maximum velocity method. The diameter so designed using the minimum velocity method incurred a minimum head loss as compared to maximum velocity method where the losses incurred are variably high. The overall total head loss was calculated using the Bernoulli's equation. The elevation losses is the same as the existing condition whereas the minor losses were assumed 10% of the major losses and the major friction losses were determined using the Darcy–Weisbach equation.

Thus the minimum velocity method of diameter design is suggested for the newly planned design of the HAC farm as compared to maximum velocity method based on the determination and analyzes of total head losses.

4. CONCLUSION

The given case study discusses about the existing pipeline network at the HAC farm. The various losses incurred in the existing pipeline network were determined. The elevation losses of the network were determined using survey process using various instruments. The minor losses incurred in the pipeline network were assumed to be 10% of the major losses. The major friction losses were determined using the Darcy–Weisbach equation.

Based on the existing diameter and its losses that are incurred, a newly method of pipeline network was suggested based on the Velocity method of optimum pipe selection. The method assumes a constant velocity range of 1.5 m/S to 3 m/S assuming a minimum and maximum velocity for the fluid flow process. The incurred losses estimated using this method was also determined and the diameters were compared based on the losses incurred. The minimum velocity method based designed diameter is considered to be an optimum solution as compared to the maximum velocity method, since it incurred much head loss as compared to the other method. The given study considers only the head loss as the objective function for the design of the optimum pipe solution between the two methods. The economic analyses of the pipe selection can also be further considered in the future as an objective function for the pipe selection. Moreover, newly suggested methods of optimum pipe design can also be considered.

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