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Flow Path Trajectory and Pressure Loss in a Water Monitor Design

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Abstract

To be effective, a fire fighting water monitor requires the maximum delivery of water onto the targeted fire source. Most commercial water monitors have a flow capacity of up to 2500 gallons per minute (GPM) and a diameter of four inches. To meet the market demand of even higher capacity flow rates, the design issues of a two degree of freedom six inch diameter water monitor with a flow capacity of 3000 GPM is investigated. To maximize the water flow rate in a designed system, the loss of water pressure in the monitor needs to be minimized. A computational fluid dynamics (CFD) tool is used to study the effect of flow path trajectory on the pressure loss in a flow system. The flow path is defined by two radial arcs tangent to each other. For a set of the flow parameters and a given flow area, the loss of water pressure is computed. The correlation between pressure loss and path geometry is used to determine the optimal path radii. This paper presents the determination of optimal path radii of the flow system and corresponding system design. The designed system achieved a 34% improvement in pressure loss compared to standard commercial designs.

Introduction

A water monitor allows for the effective discharge of water at a desired rate and a pattern for extinguishing a fire. While it is mostly inactive in its functional life, its performance in case of fire is critical in saving lives and property. There are a large variety of water monitors available on the market. Their capacities vary from a few hundred gallons to thousands of gallons per minute (GPM) of discharge. Most of these designs are of two or more degrees of freedom to allow for the manoeuvring of the water trajectory toward the fire. Each rotational degree of freedom is actuated by a manual, hydraulic, or electrical motor driven mechanism. The range of motion can vary from limited degrees to wide rotational swipe depending on the application requirement. Stationary water monitors are designed to operate as part of a fixed firefighting system near a substantial source of fire risk due to flammable liquids or gas (such as a refinery, fuel depot, chemical plants, etc.). Mobile water monitors are used in the field where they are moved around the fire such as, pumper and aerial ladder trucks. In majority of the designs, the inlet of the monitor varies from 3.5 to 4 inch in diameter with an operating pressure of 500 psi delivering about 2500 GPM of water onto the fire. The monitors are made of a suitable metal alloy, such as brass or a hard anodized aluminium with an improved surface roughness. The cross section of the waterway can be circular or elliptical with or without a vane. The goal of these features is to improve the flow and reduce the pressure loss. These monitors are intended for manual and electronic control of the water jet. Some monitors are remotely controlled for use in industrial applications where salt water and other corrosive materials may be a negatively influencing factor for pumper trucks and de-icing vehicles. A typical water monitor operating 250 psi and delivering 2500 GPM has a pressure loss of about 60 psi. Design of a water monitor depends on the hazard it is supposed to protect, thus the operational mechanism must be suitable to achieve its goal and high cost effectiveness.

Current Designs

There are a variety of water monitors available to meet the demand of each type of firefighting applications. Each design specializes in meeting the demand of a certain segment of the market. There are many features that can be considered for selection of a water monitor, such as degree of freedom, mode of operation, pressure, flow rate, size, weight, material, reliability, pressure loss and cost. The Elkhart Brass Scorpion 8294 series (Fig. 1) water monitor [1] is designed for aerial firefighting application at a pressure of 200 psi and flow rate of 2000 GPM. Its waterway is fully vaned for efficient discharge of water at 360 degree horizontal and 135 degree vertical rotation of the discharge head. Figure 2 shows the performance features of the monitor at a different flow rate. Total static pressure loss varies from 13 psi at 1000 GPM to 51 psi at 2000 GPM of water flow rate.

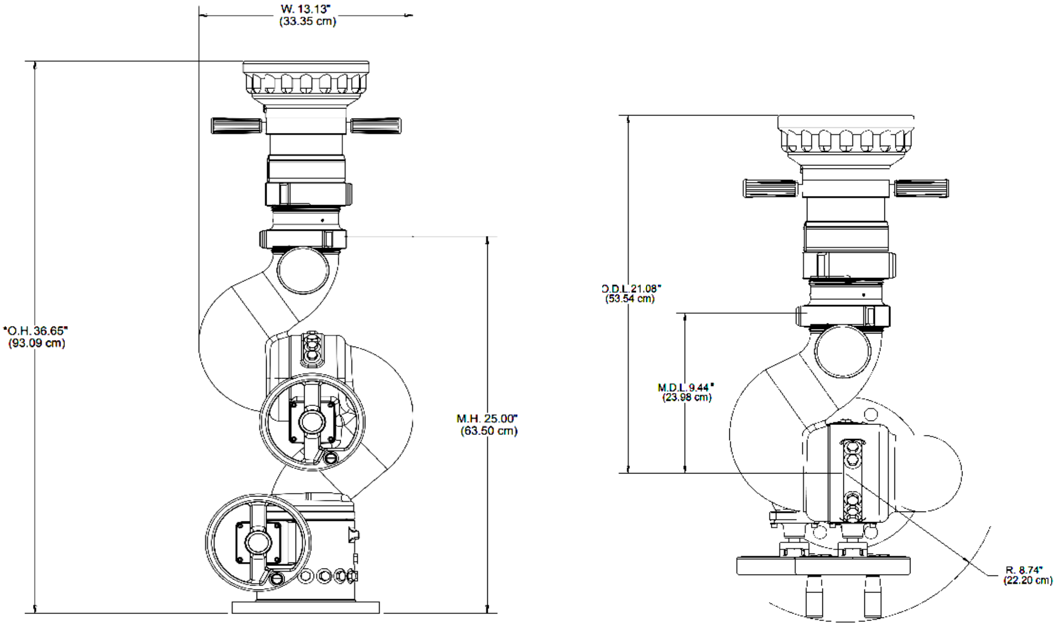

Fig. 1. Configurations of Elkhart Brass scorpion 8294 series monitor

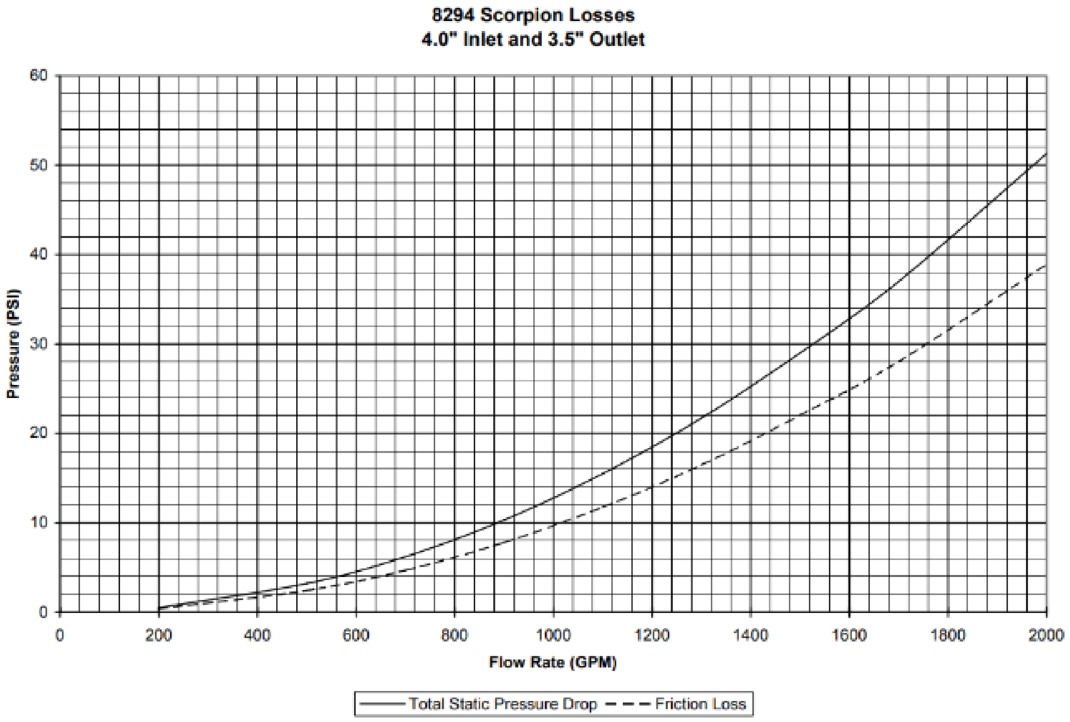

Fig. 2. Performance characteristics of Elkhart Brass scorpion 8294 series monitor

The Akron Brass 3690 Storm Monitor [2] features a 5-inches nozzle and allows for full 360 degree rotation of monitor head. The vertical travel for this monitor goes from +85 degrees to -45 degrees for a total range of 130 degrees. It is made from brass with a capacity of 2,000 GPM and is controlled with hand wheels (Figure 3).

Fig. 3. Storm series 3690 and 3698 programmable monitors

StreamMaster II (Fig. 4) is another water monitor from Akron Brass Company [3]. It has a 6-inch operating envelope which is very compact in its current design. This monitor can flow up to 2000 GPM and allows almost a full rotation (355 degrees) and an elevation range of 165 degrees; ranging from +120 degrees to -45 degrees. The StreamMaster II monitor also features a remote control system which allows the user to be at a safe distance when operating the monitor with the use of a hand-held controller. The friction loss for this design ranges from almost 0 psi at 250 GPM, up to 42 psi at 2,000 GPM (Figure 4). It has an outlet nozzle that ranges from 2.5 to 3.5 inches and works as a 12 or 24 Volt unit. This monitor is made of lightweight Pyrolite material that has excellent characteristics for wet applications.

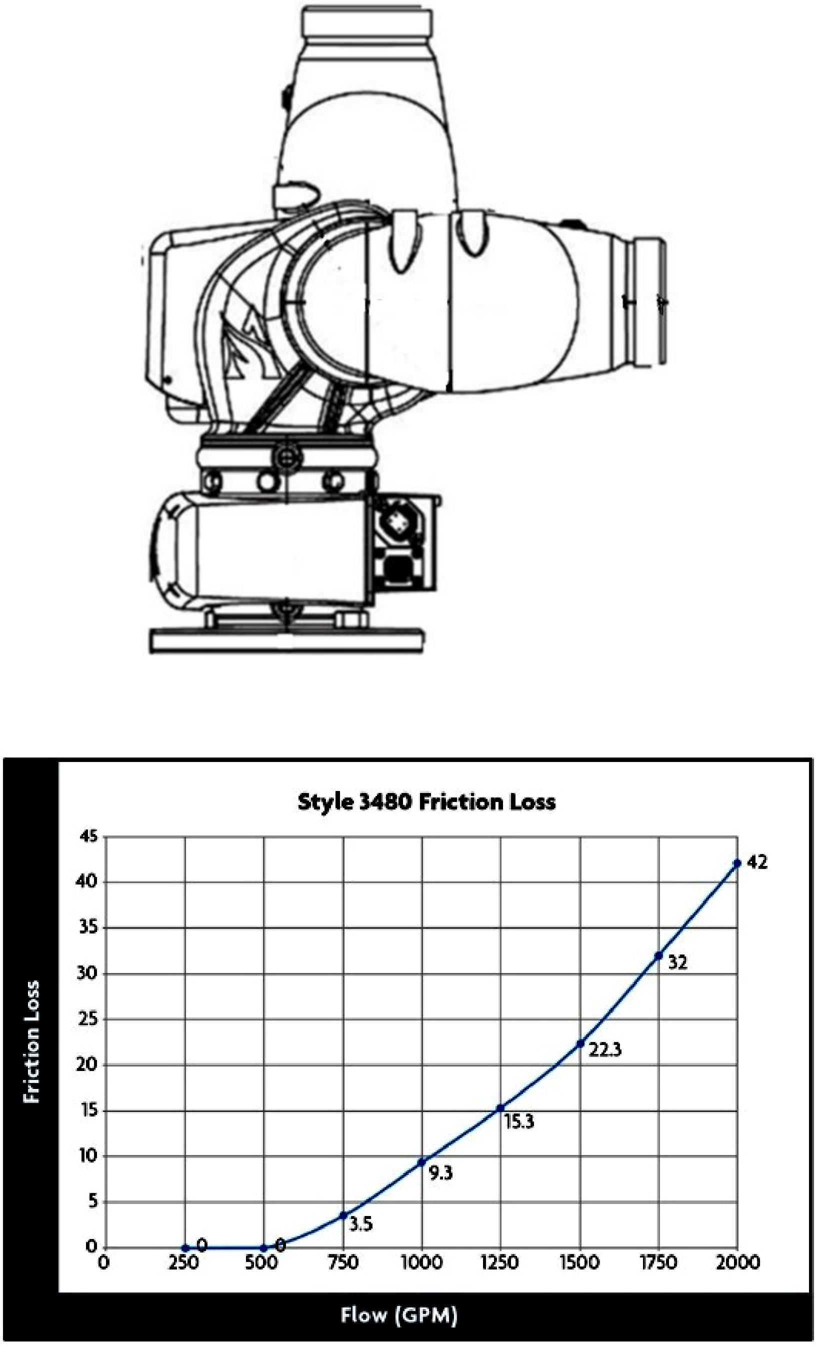

Fig. 4. StreamMaster II 3480 monitor and friction loss.

Among more recent designs, Williams Fire has one of the few 6-inch monitors that are on the market today. Their largest monitor is a direct-mount electrically actuated monitor [4]. It offers six and eight inch stainless steel waterway for maximum flow efficiency, minimum friction loss, and longer product life. It can pump water or foam up to 6,000 GPM at 200 psi pressure with 360 degree horizontal and 140 degree vertical rotation. It is controlled remotely for safe operating of the monitor. The monitor and its controls are designed to work in conditions as low as -20 degrees Fahrenheit and at a maximum working pressure of 200 psi. The pressure drop in the 6-inch monitor is 16.7 psi at 3,000 GPM and 21.2 psi at 6,000 GPM for the 8-inch monitor. The monitor is made of stainless steel and the other components are made from bronze and nickel plated brass. Model 5 Water Powered Oscillating Monitor [5] is a high flow type (750 to 1500 GPM). The oscillating mechanism is driven by a water drive wheel that is connected to a double reduction gearbox. The monitor ranges from +80 degrees to -40 degrees vertically and allows for full 360 degree rotation horizontally. It has a 4-inch nozzle and has a pressure loss from approximately 0 psi at 435 GPM to 13 psi at 1500 GPM. Performance comparison of these monitor and a new design will demonstrate the merit of the design based on flow path trajectory.

Need for design

Currently, these monitors are offered to original equipment manufacturer (OEM) of fire trucks and industrial fire protection industries in the United States with a wide variety of options capable of spraying large volumes of water at a very high rate of speed. The market demands for a small, compact, lightweight, and large-flow monitor that can be mounted on the top of a fire truck or end of an aerial ladder to deliver water using a pump that has adequate power and adheres to space limitations. One solution would be a new monitor that will flow over 3,000 GPM, but would be more compact than the 2,000 GPM monitors. The new design would also be lightweight with a small physical working envelope, such as those in industrial fire protection systems. These systems are typically multi-monitor systems that are all controlled at one or more remote locations. These monitors, unlike when used on-board a fire truck, are primarily used to blanket an area or object with water or fire-retardant foam. This application requires that the monitor withstands harsh weather conditions and prolonged usage at maximum pressure and flow. The monitor must also be made of a material compatible with environmental hazards and chemicals, as well as any chemicals that are used to create fire retardant foam.

Though the most significant factor in performance of a water monitor has traditionally been a loss of pressure, more recently the focus has been on materials, operational requirement and manufacturing cost [6]. Loss of pressure affects the flow velocity and flow rate, impacting the firefighting capability of a system negatively. In this paper, we present a study on the nature of pressure loss and its relationship with flow path trajectory. The goal is to determine the optimal flow path geometry that would be used as the basis for a design of a water monitor to achieve all other design criteria. The monitor will have a maximum friction loss of 18 psi at the rated flow of 3,000 GPM. The maximum working pressure will be 250 psi and have a static pressure of 500 psi. The performance of the new design will be compared to that of an existing Scorpion EXM monitor.

Conceptual Model

Once all the important topological features of the monitor were identified, a parametric solid model of the flow system was developed in Solidworks. The final solid model is composed of two flow guide elements, a flanged base, and flow nozzle at the end. The flow path is defined by two bend radii tangents at the intersection. The circular cross section of the flow path is swept along the flow trajectory to generate the shell and vane element of the flow system. The model is constrained by the overall size of the envelope and is in compliance with geometric features of all standard fittings of a monitor. The solid models were used to analyse water flow characteristics with the radii of primitive arcs as variables in the mathematical model. Flow elements and assembly of the design primitives are shown in Figure 5

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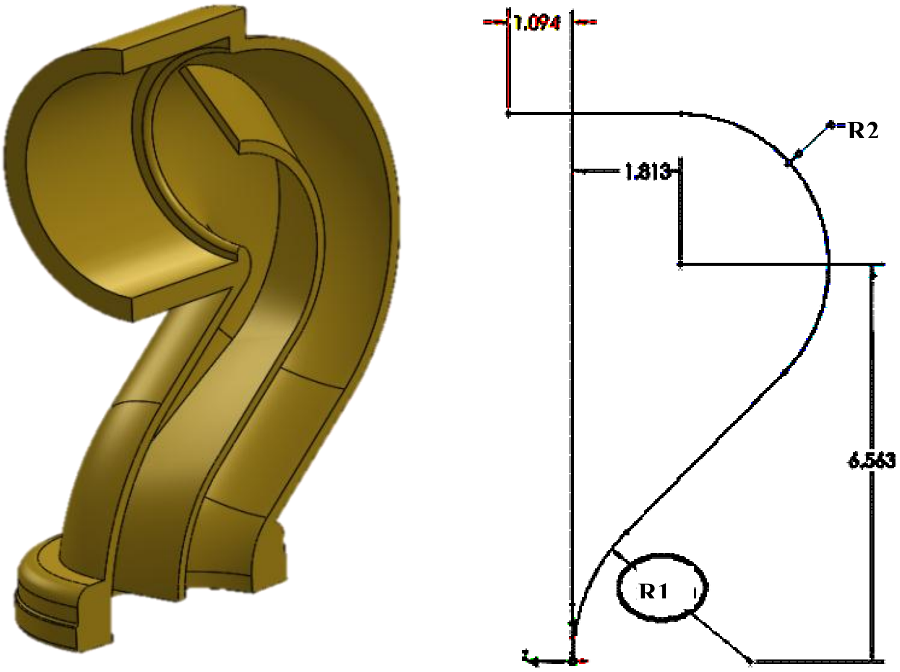

Fig. 5. Conceptual model of a vaned monitor and flow path primitives.

Design Analysis

The fluid flow characterization in most hydraulic systems can be derived from the Navier Stokes equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho V) = 0 \quad \dots. (1)$$

Where, ρ = density, V = flow velocity vector divergence operator of a general flow field.

Considering energy loss in a flow system, equation (1) for one dimensional fluid flow simplifies as Bernoulli's equation [7]

$$\frac{P_1}{\gamma} + z_1 + \frac{V_1^2}{2g} - h_L = \frac{P_2}{\gamma} + z_2 + \frac{V_2^2}{2g} \quad \dots. (2)$$

where h_L is head loss between the inlet and exit of a flow conduit.

Based on flow criteria in the system, equation (2) can be used to calculate pressure loss ΔP as

$$\Delta P = \gamma\, h_L \quad \dots. (3)$$

Since, the flow rate and pressure are function of geometry, temperature, and other fluid properties, in general, pressure loss can be expressed as a nonlinear function of n different parameters of the flow process given by

$$\Delta P = F\ (q_1, q_2, q_3, q_4, \ldots q_n) \quad \dots. (4)$$

where q represents different flow system parameters. Analysis of such flow system can be tedious for a undergraduate level design project. The study of pressure loss in a standard 90-degree bend [8] shows that the loss can be minimized by increasing the bend radius in general. But dimensional constraints of the water monitor volume envelope, beyond a certain radius, where this pressure loss starts increasing [9].

In this paper, a numerical method Computational Fluid Dynamics (CFD) is applied to determine optimal design parameters. Parametric CFD [10] is used in both the conceptual and improvement stages of a design process to validate or rectify a particular design.

The final assembly of the monitor solid model was utilized to analyse the flow problem at different pressures and flow rate of water using the integrated Computational Fluid Dynamics (CFD) analysis tool in SolidWorks. The eventual goal of the analysis is to design a six in diameter monitor at 3000 GPM flow. Since performance of the current comparable model at 1250 GPM flow rate and 100 psi pressure is known, analysis presented here is under identical scenario. A programming tool was developed to automatically perform this analysis for a combination of the flow trajectory radii. The analysis was conducted by varying the two radii of the flow path trajectory one at a time. Theoretically, pressure loss in a closed conduit in turbulent flow increases with the length of the path, but decreases with the curvature radius [6]. But as the path radius is increased, the length of the path also increases. Therefore, net loss of pressure due to friction depends on the combined effect of the path radius and length.

An input pressure of 100 psi at the entrance of the flow monitor (i.e. lower end) and a 1,000 GPM flow rate of water at 60^0F was specified. Typical surface roughness of cast aluminium (100 μ inch) was used for surface friction of the monitor. The first radius (R1) was varied from 2.75in to 4.625in, and the second radius (R2) was varied from 2.25in to 3.25in at finite steps. The CFD tool utilizes flow parameter to compute average pressure at the end under the given conditions. A total of 34 different combinations of path radii were used in this analysis. Table I shows pressure at the end of the flow path and pressure loss at different trajectory radius. It revealed a clear correlation between the path radius and pressure at monitor exit (Fig. 6).

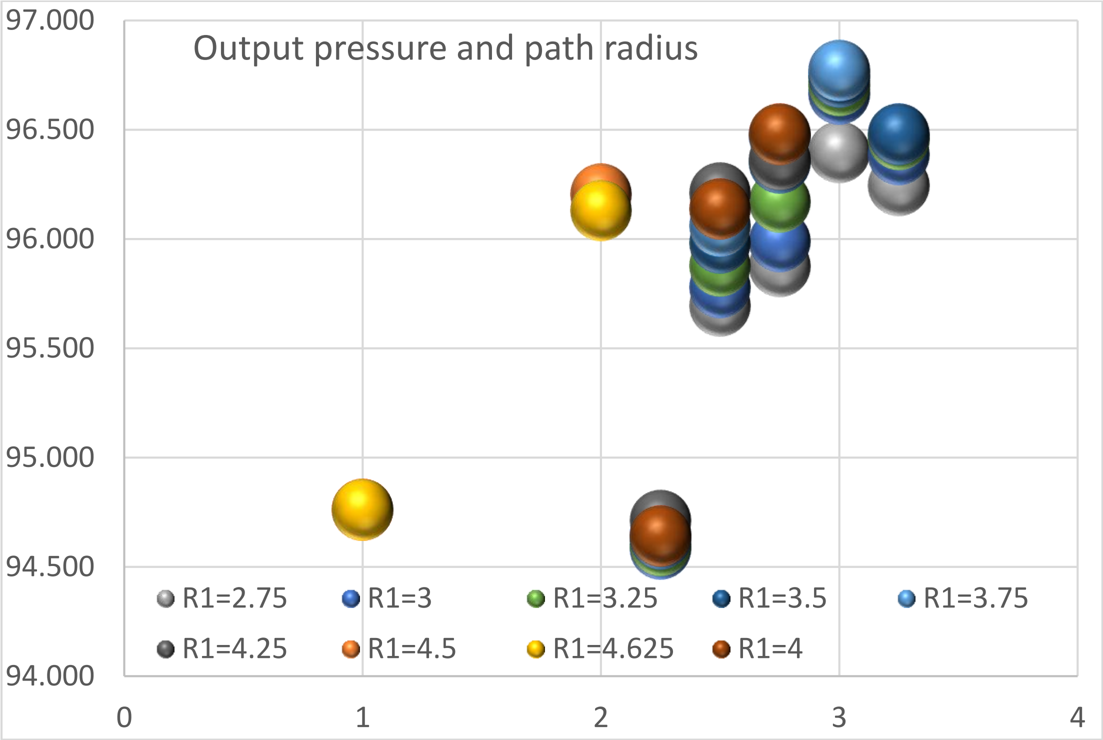

Fig. 6. Pressure and path radius correlation.

As expected, the trend is as the radius R1 and R2 are increased pressure at the end of water path increases and pressure loss decreases. Because of limitations in the envelope size, to optimize the path trajectory, these radii could not be increased indefinitely. Figure 7 presents the effect of path radius on pressure loss. The lowest pressure loss was 3.229 psi at R1=3.75 and R2=3 inches depicted in green in Table I.

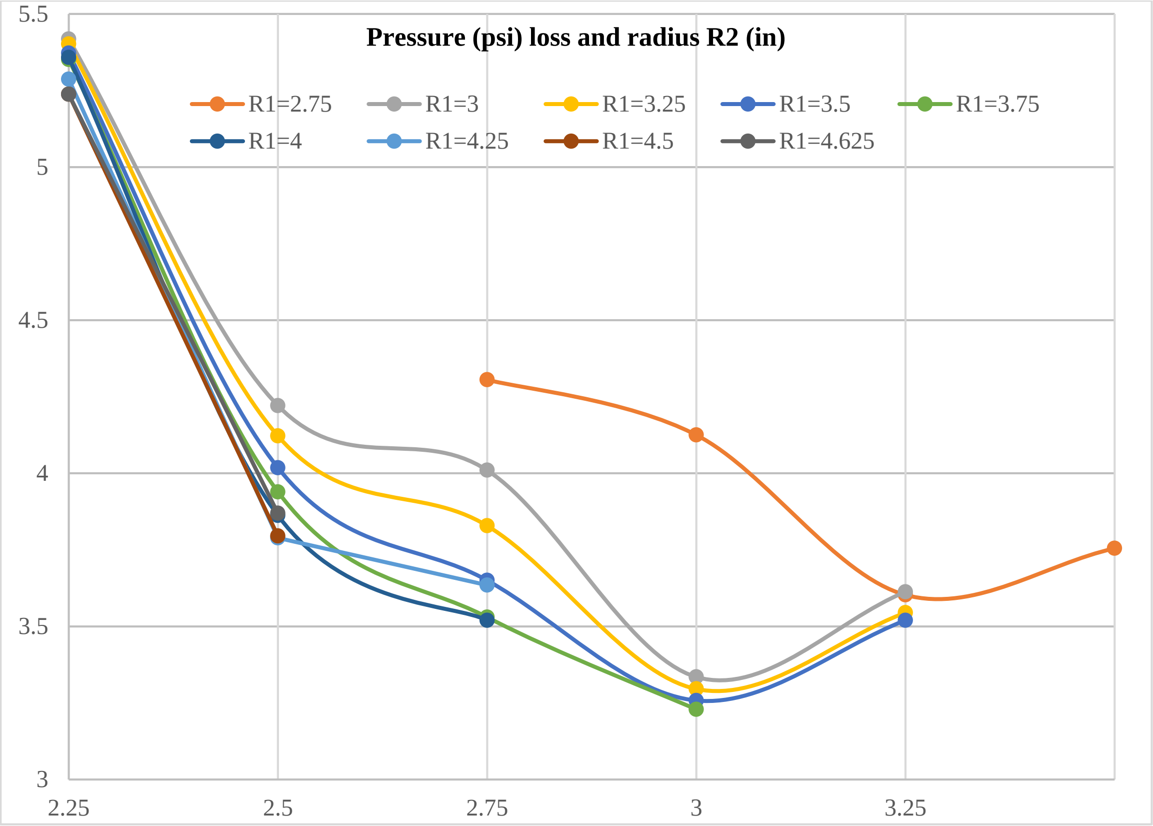

Fig. 7. Pressure loss and path radius

This study was continued by adding a vane in the solid model. Though the addition of vane decreases cross sectional area of the flow path, in turbulent flow, it actually decreases pressure loss even further. The next effect of the cross section shape on pressure loss was investigated. Instead of the circular section, the use of elliptical section produces less pressure loss. But additional manufacturing costs for the elliptical surface does not justify the use of the noncircular section of the water way. Eventually, under the same boundary conditions, compared to 22.311 psi pressure in existing Scorpion EXM monitor, this optimized monitor shows a pressure loss of 14.661 psi, a

34% improvement in performance. After the addition of all machining and assembly features for the support base, nozzle, instrumentation, and drive mechanisms in the solid model, a complete assembly model for the water monitor is shown in Fig. 5.

Figure 5. Complete assembly of optimized model.

Table I: Output pressure and pressure loss

Config #	R1 (in)	R2 (in)	Output Pressure (psi)	Pressure loss (psi)
1	2.75	2.25	89.963	10.037
2	2.75	2.5	95.695	4.305
3	2.75	2.75	95.875	4.125
4	2.75	3	96.397	3.603
5	2.75	3.25	96.245	3.755
6	3	2.25	94.582	5.418
7	3	2.5	95.779	4.221
8	3	2.75	95.990	4.010
9	3	3	96.665	3.335
10	3	3.25	96.387	3.613
11	3.25	2.25	94.598	5.402
12	3.25	2.5	95.878	4.122
13	3.25	2.75	96.171	3.829
14	3.25	3	96.704	3.296
15	3.25	3.25	96.455	3.545
16	3.5	2.25	94.628	5.372
17	3.5	2.5	95.982	4.018
18	3.5	2.75	96.350	3.650
19	3.5	3	96.742	3.258
20	3.5	3.25	96.480	3.520
21	3.75	2.25	94.649	5.351
22	3.75	2.5	96.061	3.939
23	3.75	2.75	96.470	3.530
24	3.75	3	96.771	3.229
25	4	2.25	94.642	5.358
26	4	2.5	96.138	3.862
27	4	2.75	96.480	3.520
28	4.25	2.25	94.713	5.287
29	4.25	2.5	96.211	3.789
30	4.25	2.75	96.365	3.635
31	4.5	2.25	94.762	5.238
32	4.5	2.5	96.205	3.795
33	4.625	2.25	94.762	5.238
34	4.625	2.5	96.131	3.869

CONCLUSIONS

A four-inch water monitor was designed to deliver 3000 GPM of water. The most significant improvement was due to the flow path trajectory defined by segmented arc primitives. The specified goal for the improvement of flow and pressure loss were accomplished. In the CFD analysis, this new design reduces the pressure loss by more than 34% compared to an existing model. The performance of the system was further improved by the use of low friction surface treatment. After its performance testing, this design would be refined prior to commercial production.

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