MONTANA STATE UNIVERSITY

Department of Mechanical and Industrial Engineering

EGEN 435: Fluid Dynamics

Tiered Hydroponic Pipe System

Final Report

By

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Abstract

Tiered, vertical, indoor hydroponic farms are a rapidly growing industry. With cities growing larger and farms located further away, the need for fresh, locally grown greens is in more demand than ever. Indoor vertical farms allow for large amounts of growing area located in a small footprint. However these farms require large, complex pipe systems in order to feed the plants, nutrients and water.

Introduction

For this project, I've chosen to model a 3 tiered vertical hydroponic pipe system. This system comprises of a total of 36 free jets, each filling a 40 gallon tank with a solution of water and plant nutrients. In order to allow for maximum efficiency, the system will need to fill the tank in less than 10 min. The top tier of the system will be at an elevation of 15 ft above the ground with each tier separated by 5.5 ft (Figure A.1). The energy equation, paired with the Swami Jane approximation will be used to calculate the necessary pump head and flow rate. The solver will be built into an excel spreadsheet. When completed, the solver will easily allow for pipe system parameters to be changed. In essence, the scope of this project is to create a design tool for a specialized piping system.

Methodology & Setup

In order to ensure success, several assumptions have to be made to help simplify the problem. Some of these assumptions include; system is at steady state, all free jets have the same flow rate, water is working fluid, friction factor is not constant, and water is being pulled from a large reservoir. Most of these assumptions are straight forward, however, the assumption that all free jets have the same flow rate would merit further explanation. This assumption means that the major losses due to plumbing between each free jet does not affect the flow rate of the jets. Once these assumption are made, the energy equation (Figure A4) becomes significantly simpler. The simplified version of the energy equation will be the governing equation for the solver. The Swami Jane approximation (Figure A5) will be used to calculate the friction factor for each pipe and flow rate.

To make the problem manageable, the system will be broken down into three different subsystems (Figures A1-A3). Also, a numbering system will be incorporated to allow for ease of calculation. Furthermore, the solution becomes even more simplified due to the nature of the flow through the system. Because a large majority of the flow is considered parallel, the summation of the minor and major head losses becomes much simpler. We can see in figures A6-A8, flow in parallel does not need to have head loss summed. This means that we need only to calculate the head loss from a fraction of the total pipes and fittings in the system. These methods are then incorporated into a sheet that calculate the major and minor head losses for the system (Figure A11).

To ensure each tear will produce the same flow rate, control valves will be placed on the end of each free jet. These valves will help account for the elevation changes of each tier. To calculate the control valve settings, minor loss coefficient data for a butterfly valve (Figure A9) was obtained from Larock[1]. This data will be used to solve for the required control valve settings for each tier to make up for elevation changes (Figure A10). To solve for the required %Open for each tier, a target head loss value obtained by declaring the height of each valve and then subtracting that height from the highest point in the system. Then the minor head loss of the valve is determined by inputting an approximate value for percent open and flow rate. Using these parameters and the data from figure A9, a minor loss coefficient is determined using excel interpolation function. These parameters are then fed into the total system head loss calculations. Because determining the control valve settings requires estimation of some parameters, an iterative process is required to converge on the system operating conditions. In order to expedite this process, a macro controlled goal seek function is assigned to each of the two sheets (Figures A10&A11).

Results

The overall results of the solver seem reasonable. With the system operating conditions and control valve settings seen in Table 1. However, it is worth noting that the results from this system have not been verified, neither experimentally or analytically through a third party application such as CFD. Moreover, the assumptions discussed in the Methods & Setup section likely have a large impact on the solution. For this reason, I believe more investigation and refinement would be needed before the solutions for this solver can be trusted.

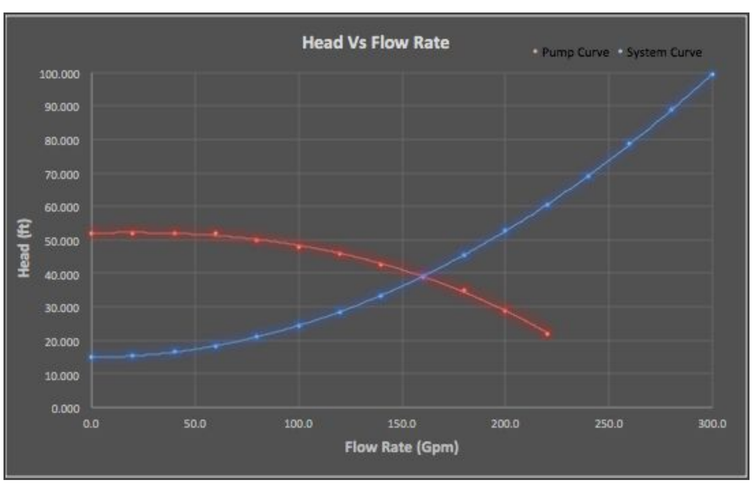


Figure 1: Pump and System Curves.

Table 1: System operating conditions and Control Valve settings.

Operating Flow Rate	160 Gpm
Operating Head	39 ft
Control Valves Tier 1 (% Open)	15.9%
Control Valves Tier 2 (% Open)	17.1%
Control Valves Tier 2 (% Open)	99.9%

Appendix A:

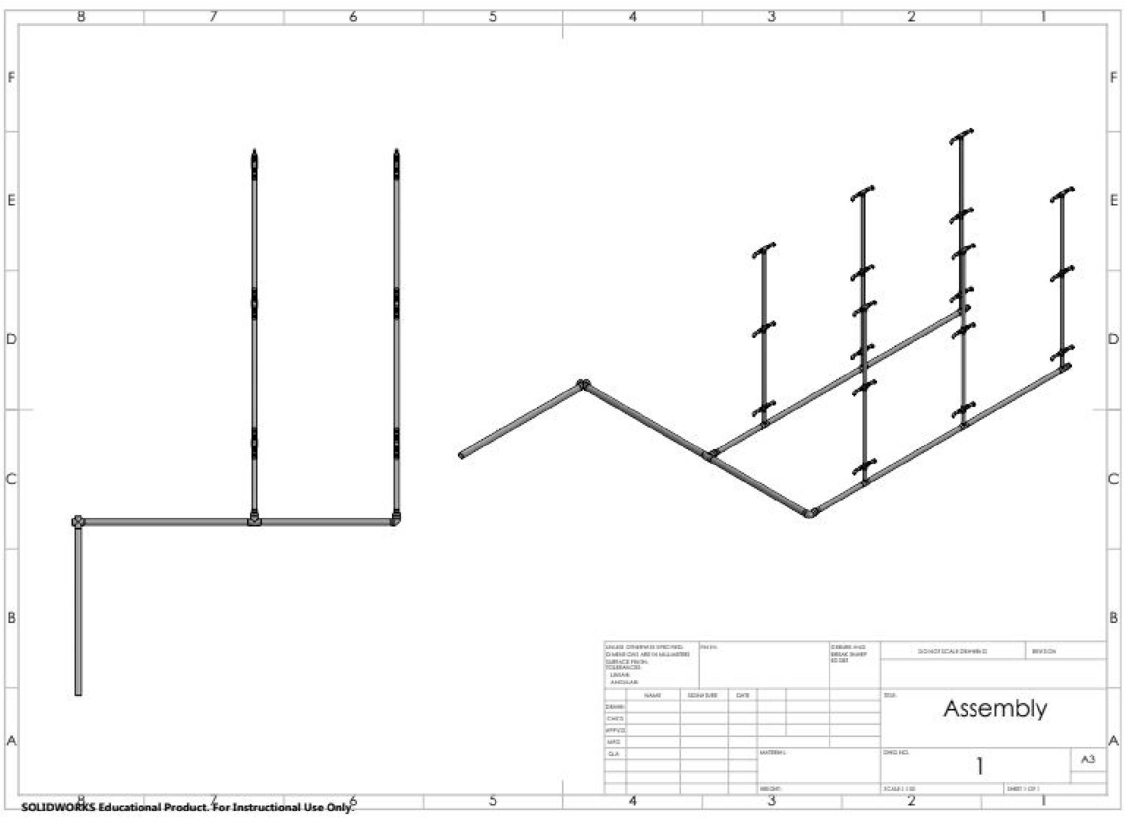


Figure A.1: System Assembly

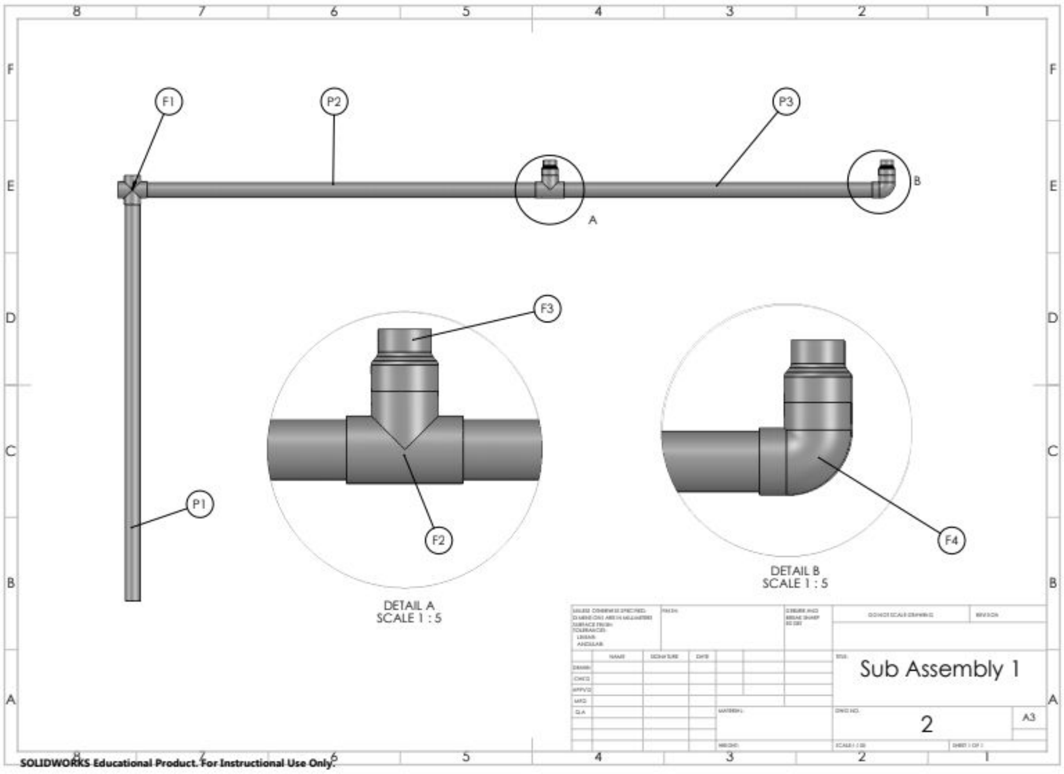


Figure A2: System Subsection/Sub Assembly 1.

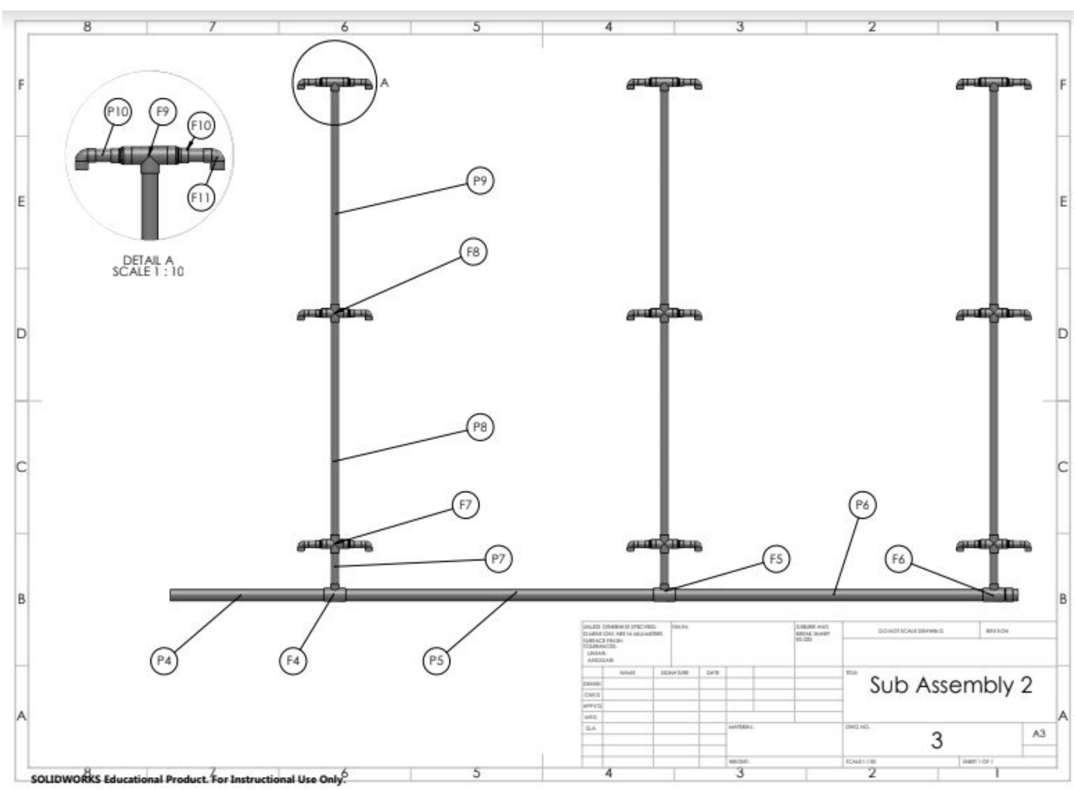


Figure A3: System subsection/sub assembly 2.

$$\frac{P_e}{\gamma} + \frac{V_i^2}{2g} + z_i + h_p = \frac{P_e}{\gamma} + \frac{V_e^2}{2g} + z_e + h_f + h_m$$

$$\frac{P_e}{\gamma} + \frac{V_i^2}{2g} + z_i + h_p = \sum_{e=1}^{n}\left(\frac{P_e}{\gamma} + \frac{V_e^2}{2g} + z_e\right) + \sum_{e=1}^{n}\left(f\,\frac{l}{D}\frac{V_e^2}{2g}\right) + \sum_{e=1}^{n}\left(K_L\,\frac{V_e^2}{2g}\right)$$

$$h_p = \sum_{e=1}^{n}\left(\frac{V_e^2}{2g}\right) + \sum_{e=1}^{n}\left(f\,\frac{l}{D}\frac{V_e^2}{2g}\right) + \sum_{e=1}^{n}\left(K_L\,\frac{V_e^2}{2g}\right) + z_t$$

Figure A4: Energy equation.

$$\frac{1}{\sqrt{\lambda}} \approx -2 \cdot \log_{10}\left(\frac{\varepsilon}{3.7 \cdot D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)$$

Figure A5: Swami Jane approximation.

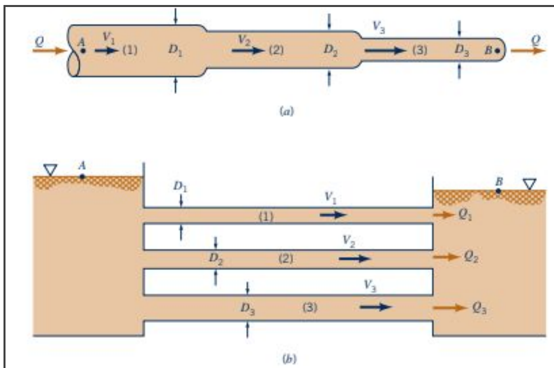


Figure 8.35 (*a*) Series and (*b*) parallel pipe systems.

Figure A6: Parallel and Series flow[2].

$$Q_1 = Q_2 = Q_3$$

$$h_{L_{A-B}} = h_{L_1} + h_{L_2} + h_{L_3}$$

Figure A7: Series flow summation[2].

$$Q = Q_1 + Q_2 + Q_3$$

$$h_{L_1} = h_{L_2} = h_{L_3}$$

Figure A8: Parallel flow summation[2].

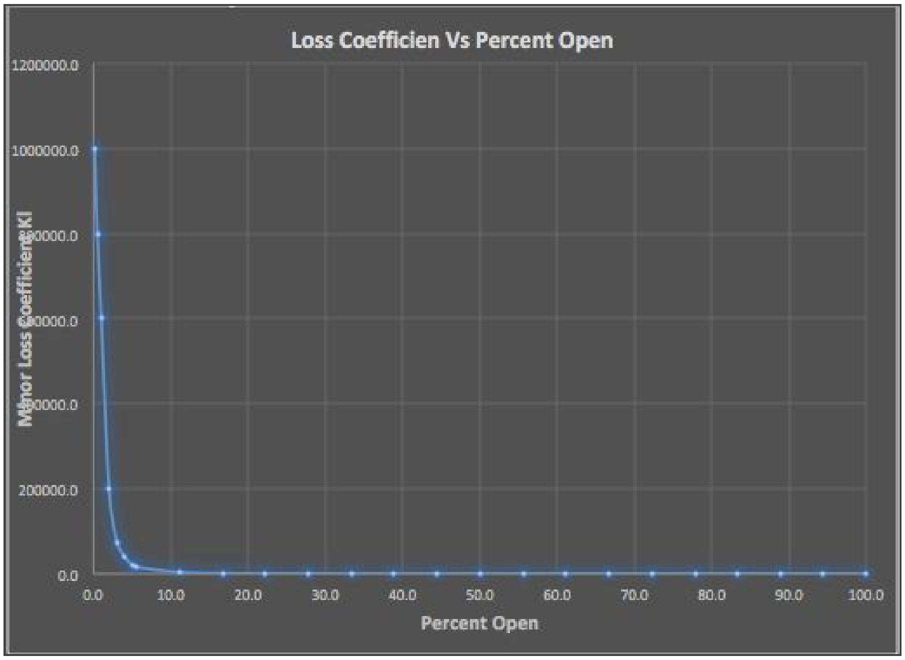


Figure A9: Loss Coefficient Vs. Percent Open.

Constants	
Density (slug/ft^3)	1.94
Kinematic Viscosity (ft^2/s)	1.22E-05
Gravity (ft/s^2)	32.2
Pump Present (yes=1/no=0)	1
Operational Flow Rate (Gpm)	159.9
Operational Flow Rate (Cfs)	0.35625868
Total Number of Free Jets	36
Elevation Change	
Z1 (ft) Daytum	0
Z2 (ft) Max Hight	15
Control Valves	
CVT1	
Free Jets being fed	1
Diameter (ft)	0.125
Hight from Datum (ft)	1.5
Target Head Loss (ft)	13.5
Percent Open	15.9304643
Minor Loss Coefficent	1336.945
Velocity (ft/s)	0.80640469
Total Head Loss (ft)	13.5
Difference in Hl	0
CVT2	
Free Jets being fed	1
Diameter (ft)	0.125
Hight from Datum (ft)	6
Target Head Loss (ft)	9
Percent Open	17.1019537
Minor Loss Coefficent	891.296667
Velocity (ft/s)	0.80640469
Total Head Loss (ft)	9
Difference in Hl	0
CVT2	
Free Jets being fed	1
Diameter (ft)	0.125
Hight from Datum (ft)	15
Target Head Loss (ft)	0.00451599
Percent Open	99.9
Minor Loss Coefficent	0.44723214
Velocity (ft/s)	0.80640469
Total Head Loss (ft)	0.00451599

Valve Minor Loss Closing Data		
% Open	Degrees Open	Kl
0.1		999999.0
0.5		800000.0
1.0		600000.0
2.0		200000.0
3.0		75000.0
4.0		42000.0
5.0		20000.0
5.6	5.000	15625.0000
11.1	10.000	3860.0000
16.7	15.000	935.0000
22.2	20.000	337.0000
27.8	25.000	145.0000
33.3	30.000	71.8000
38.9	35.000	39.6000
44.4	40.000	21.6000
50.0	45.000	12.7000
55.6	50.000	7.4200
61.1	55.000	4.4100
66.7	60.000	2.6400
72.2	65.000	1.5900
77.8	70.000	0.9520
83.3	75.000	0.6200
88.9	80.000	0.4960
94.4	85.000	0.4600
100.0	90.000	0.4470

Calculate

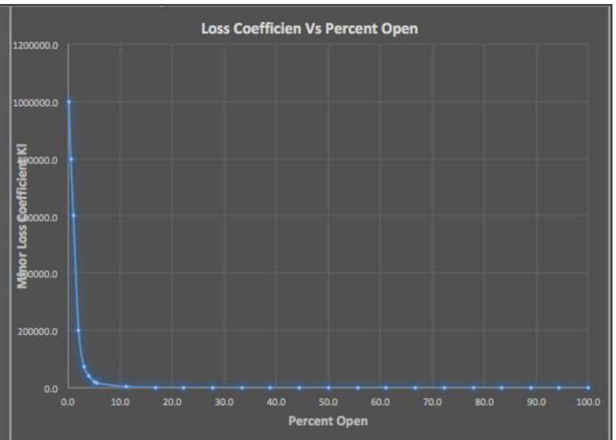


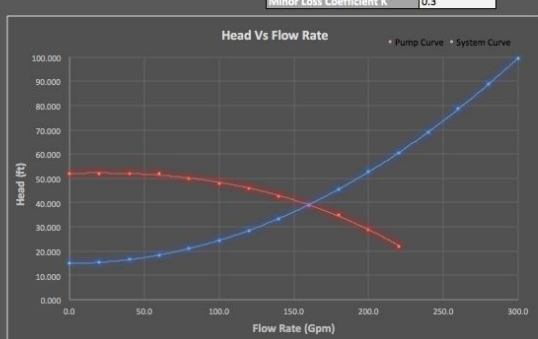
Figure A10: Control Valve Setting Calculations.

Constants		
Density (slug/ft^3)	1.94	
Kinematic Viscosity (ft^2/s)	1.22E-05	
Gravity (ft/s^2)	32.2	
Pump Present (yes=1/no=0)	1	
Min Vol. Flow Rate (Gpm)	0.00001	
Max Vol. Flow Rate (Gpm)	400	
Total Number of Free Jets	36	
Elevation Change		
Z1 (ft) Daytum	0	
Z2 (ft) Max Hight	15	
Pump Curve Data		
Q (gal/min)	Q (cfs)	Hp
0.0	0.000	52.000
20.0	0.045	52.000
40.0	0.089	52.000
60.0	0.134	52.000
80.0	0.178	50.000
100.0	0.223	48.000
120.0	0.267	46.000
140.0	0.312	42.500
160.0	0.356	39.000
180.0	0.401	35.000
200.0	0.446	29.000
220.0	0.490	22.000
240.0	0.535	0.000
260.0	0.579	0.000
280.0	0.624	0.000
300.0	0.668	0.000
320.0	0.713	0.000
340.0	0.758	0.000
360.0	0.802	0.000
380.0	0.847	0.000
400.0	0.891	0.000

Calculate

System Operating Conditions		
Q (Gpm)	Q (cfs)	Head (ft)
159.9	0.356	39.092

Sub Assembly 1			
Pipes		**Fittings**	
P1		**F1**	
Number	1	Number	1
Free Jets being fed	36	Free Jets being fed	36
Length (ft)	10	Upstream Pipe Diameter (ft)	0.333333333
Diameter (ft)	0.333333333	Minor Loss Coefficient K	0.5
Roughness e	0.000005	**F2**	
P2		Number	1
Number	1	Free Jets being fed	36
Free Jets being fed	36	Upstream Pipe Diameter (ft)	0.333333333
Length (ft)	8	Minor Loss Coefficient K	1
Diameter (ft)	0.333333333	**F3**	
Roughness e	0.000005	Number	1
P3		Free Jets being fed	18
Number	1	Upstream Pipe Diameter (ft)	0.333333333
Free Jets being fed	16	Minor Loss Coefficient K	0.3
Length (ft)	8	**F4**	
Diameter (ft)	0.333333333	Number	1
Roughness e	0.000005	Free Jets being fed	18
		Upstream Pipe Diameter (ft)	0.333333333
		Minor Loss Coefficient K	0.3



Sub Assembly 2			
Pipes		**Fittings**	
P4		**F4**	
Number	1	Number	1
Free Jets being fed	18	Free Jets being fed	18
Length (ft)	8	Upstream Pipe Diameter (ft)	0.25
Diameter (ft)	0.25	Minor Loss Coefficient K	0.2
Roughness e	0.000005	**F5**	
P5		Number	1
Number	1	Free Jets being fed	12
Free Jets being fed	12	Upstream Pipe Diameter (ft)	0.25
Length (ft)	16	Minor Loss Coefficient K	0.2
Diameter (ft)	0.25	**F6**	
Roughness e	0.000005	Number	1
P6		Free Jets being fed	6
Number	1	Upstream Pipe Diameter (ft)	0.25
Free Jets being fed	6	Minor Loss Coefficient K	0.2
Length (ft)	16	**F7**	
Diameter (ft)	0.25	Number	1
Roughness e	0.000005	Free Jets being fed	6
P7		Upstream Pipe Diameter (ft)	0.166666667
Number	1	Minor Loss Coefficient K	0.5
Free Jets being fed	6	**F8**	
Length (ft)	1.5	Number	1
Diameter (ft)	0.16666667	Free Jets being fed	4
Roughness e	0.000005	Upstream Pipe Diameter (ft)	0.166666667
P8		Minor Loss Coefficient K	0.5
Number	1	**F9**	
Free Jets being fed	4	Number	1
Length (ft)	5.5	Free Jets being fed	2
Diameter (ft)	0.16666667	Upstream Pipe Diameter (ft)	0.166666667
Roughness e	0.000005	Minor Loss Coefficient K	1
P9		**F10**	
Number	1	Number	1
Free Jets being fed	2	Free Jets being fed	1
Length (ft)	5.5	Upstream Pipe Diameter (ft)	0.166666667
Diameter (ft)	0.16666667	Minor Loss Coefficient K	1
Roughness e	0.000005	**F11**	
P10		Number	1
Number	1	Free Jets being fed	1
Free Jets being fed	1	Upstream Pipe Diameter (ft)	0.166666667
Length (ft)	0.33333333	Minor Loss Coefficient K	0.3
Diameter (ft)	0.125	**Free Jets**	
Roughness e	0.000005	Diameter	0.125

Figure A11: Head Loss Calculations.

Appendix B: Sources

[1] Larock, Bruce E., et al. Hydraulics of Pipeline Systems. CRC Press, 2000.

[2] Munson, Bruce Roy, et al. Fundamentals of Fluid Mechanics. John Wiley & Sons, Inc., 2013.