Project 3

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[1]:
```
# Imports
import numpy as np
from scipy.optimize import fsolve
from scipy.interpolate import interp1d
from msu_esd import Pipe
import matplotlib.pyplot as plt

plt.style.use('maroon_ipynb.mplstyle')
```

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1 Given

From Project 1, piping and pump requirements for a chilled fluid circulating system for a portion of the Orlando Airport were determined. A Z-network was used for the system, and the pumps head and flow rate requirements were found.

1.1 Project 1 Overview

From Project 1, the booster pump option was selected because it was more cost-efficient and offered more control over the system. The schematic is shown in Figure 1.

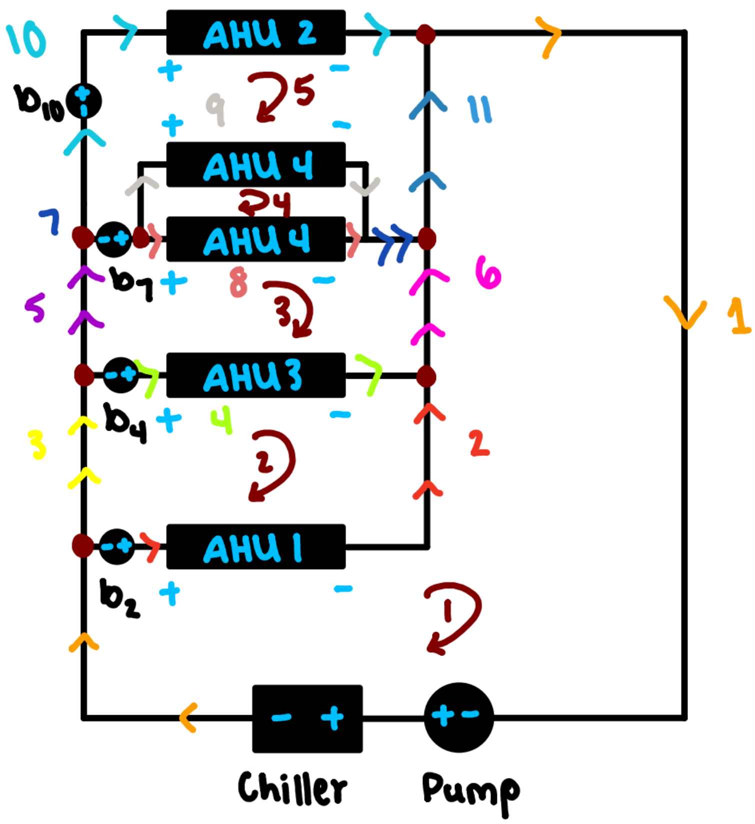


Figure 1: Booster Pump Schematic

The resulting head values are $b_2 = 67.65\,ft$, $b_4 = 101.95\,ft$, $b_7 = 55.7\,ft$, and $b_{10} = 44.9\,ft$. The main line pump has a head of $W_s = 145\,ft$. The summary of the piping lengths as well as material properties are given in Table 1.

Table 1: Summary of Piping

Pipe	L (ft)	D (in)	# Valves	# Elbows	K	C
1	2840	18.812	1	0	1.78	8
2	2380	10.02	1	5	5.53	8
3	1300	11.938	1	0	1.78	8
4	1630	10.02	1	5	5.53	8
5	3000	11.938	1	2	3.28	8
6	5000	11.938	1	2	3.28	8

Pipe	L (ft)	D (in)	# Valves	# Elbows	K	C
7	1580	11.938	1	0	1.78	8
8	1550	7.981	1	5	5.53	8
9	1550	7.981	1	7	7.03	8
10	5130	10.02	1	8	7.78	8
11	1875	11.938	1	1	2.53	8

Material: Galvanized Steel (Schedule 40)
Absolute Roughness: $\epsilon = 0.0005\, ft$
Working Fluid: Therminol D-12
Density: $\rho = 48.05 \frac{lbm}{ft^3}$
Heat Capacity: $c_p = 0.491 \frac{Btu}{lbm^{\circ}F}$
Viscosity: $\mu = 3.715 \frac{lbm}{ft\,hr}$

The system of equations using the Kirchhoff method is,

$$
\begin{cases}
Q_1 = Q_3 + Q_2 \\
Q_3 = Q_4 + Q_5 \\
Q_6 = Q_2 + Q_4 \\
Q_5 = Q_7 + Q_{10} \\
Q_7 = Q_8 + Q_9 \\
Q_{11} = Q_6 + Q_7 \\
h_2 + K_1 Q_2|Q_2| + h_6 + h_{11} + h_1 - 150 + 0.1 Q_1|Q_1| - b_2 = 0 \\
h_4 + K_3 Q_4|Q_4| - h_2 - K_1 Q_2|Q_2| + h_3 + b_2 - b_4 = 0 \\
h_7 + h_8 + K_4 Q_8|Q_8| - h_6 - h_4 - K_3 Q_4|Q_4| + h_5 + b_4 - b_7 = 0 \\
h_9 + K_4 Q_9|Q_9| - h_8 - K_4 Q_8|Q_8| = 0 \\
h_{10} + K_2 Q_{10}|Q_{10}| - h_{11} - h_7 - h_9 - K_4 Q_9|Q_9| + b_7 - b_{10} = 0
\end{cases}
$$

The code block below outputs the flow rates for this system.

[2]:
```
# Define known constants
K1, K2, K3, K4 = 4.5, 4.5, 4.5, 10  # Loss coefficients

rho = 48.05/32.174  # In slugs per cubic feet
mu = 3.715/(3600*32.174)  # In slugs per (ft s) or lbf*s per ft squared
epsilon = 0.0005  # In ft

D20, D12, D10, D8 = np.array([18.812, 11.938, 10.02, 7.981])/12  # Diameters in
↪ft

Ws = 145  # in ft

# Define pipe objects
p1 = Pipe(D20, 2840, epsilon, rho, mu, K=1.78, C=8)
p2 = Pipe(D10, 2380, epsilon, rho, mu, K=5.53, C=8)
```

```
p3 = Pipe(D12, 1300, epsilon, rho, mu, K=1.78, C=8)
p4 = Pipe(D10, 1630, epsilon, rho, mu, K=5.53, C=8)
p5 = Pipe(D12, 3000, epsilon, rho, mu, K=3.28, C=8)
p6 = Pipe(D12, 5000, epsilon, rho, mu, K=3.28, C=8)
p7 = Pipe(D12, 1580, epsilon, rho, mu, K=1.78, C=8)
p8 = Pipe(D8, 1550, epsilon, rho, mu, K=5.53, C=8)
p9 = Pipe(D8, 1550, epsilon, rho, mu, K=7.03, C=8)
p10 = Pipe(D10, 5130, epsilon, rho, mu, K=7.78, C=8)
p11 = Pipe(D12, 1875, epsilon, rho, mu, K=2.53, C=8)

def balanced(x, b2, b4, b7, b10):
    Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q10, Q11 = x
    # all expressions need to be set to zero
    return [
        Q1 - Q2 - Q3,
        Q6 - Q2 - Q4,
        Q3 - Q4 - Q5,
        Q5 - Q10 - Q7,
        Q7 - Q8 - Q9,
        Q11 - Q6 - Q7,
        K1*Q2*abs(Q2) + p2.h(Q2) + p6.h(Q6) + p11.h(Q11) + p1.h(Q1) - Ws + 0.
 ↪1*Q1*abs(Q1) - b2,
        p4.h(Q4) + K3*Q4*abs(Q4) - p2.h(Q2) - K1*Q2*abs(Q2) + p3.h(Q3) + b2 -␣
 ↪b4,
        p7.h(Q7) + p8.h(Q8) + K4*Q8*abs(Q8) - p6.h(Q6) - p4.h(Q4) -␣
 ↪K3*Q4*abs(Q4) + p5.h(Q5) + b4 - b7,
        p9.h(Q9) + K4*Q9*abs(Q9) - p8.h(Q8) - K4*Q8*abs(Q8),
        p10.h(Q10) + K2*Q10*abs(Q10) - p11.h(Q11) - p9.h(Q9) - K4*Q9*abs(Q9) -␣
 ↪p7.h(Q7) + b7 - b10
    ]

Q_guess = np.array([5, 1, 4, 2, 2, 3, 1, 3, -2, 1, 4])  # This does satisfy␣
 ↪mass conservation
b = 67.65, 101.95, 55.7, 44.9
balanced_solution = fsolve(balanced, Q_guess, args=(*b, ))
balanced_solution  # flow rates in ft^3/s
```

[2]:
```
array([10.69253924,  2.71300891,  7.97953032,  2.7132475 ,  5.26628283,
        5.42625641,  2.55233847,  1.27984524,  1.27249323,  2.71394436,
        7.97859488])
```

2 Find

Using the results from Project 1 and the Goulds handout, accomplish the following:

a. Are viscous fluid pump corrections needed?
b. Select the required main-line pump (company, model number, RPM, rotor diameter). A copy

of the manufacturer's pump performance information is needed in the report. If booster pumps are used, then continue to use the same booster pumps increases in head as in Project 1 (the corrected version), but you do not need to specify an exact model.

c. Generate a curve fit for H vs. Q for the main-line pump of part (b). Verify using the Hardy-Cross or Kirchhoff program that the selected pump is suitable. This means that the H-Q curve fit is to be placed in the Hardy-Cross or Kirchhoff program and the resulting flow rates in the individual loads are to be computed and compared with the required flow rates. Compute the power required for the pump including viscous corrections, if needed.
d. The management team also wants a parallel pump arrangement, using identical pumps, for the main line to be examined. Booster pumps, if used, are the same as in Part (b). Select the required pump (model number, RPM, rotor diameter). A copy of the manufacturer's pump performance information is needed. Use the Hardy-Cross or Kirchhoff program to find the behavior of the system with (1) both pumps in parallel and (2) only one of the parallel pumps in operation. This gives some idea of the system capability of the parallel arrangement if one pump is down. For the parallel analysis, determine the power required (including viscous corrections, if needed) for the two parallel pump operating conditions.
e. Provide a summary of the recommended pumps for the system including the system capacity when only one of the pumps in the parallel configuration is operating. A recommendation as to which arrangement to use, single main pump or parallel main pumps, is desired.

3 Solution

3.1 Part A

The first step for determining whether viscous effects are negligible is to acquire the SSU viscosity. The code block below contains the function for finding the SSU viscosity, given the kinematic viscosity. This was added to the `msu_esd` package, but is shown here for convenience.

[3]:
```
def SSU(nu):
    """
    Returns the Saybolt Seconds Universal value of viscosity.

    :param nu: The kinematic viscosity in ft^2/s
    :return: SSU value
    """
    guess = 100
    stoke = 1e-4  # m^2/s
    nu = nu/3.28084**2  # converts to m^2/s

    if nu < 0.2065*stoke:
        return fsolve(lambda ssu: nu - 0.00226*stoke*ssu + 1.95*stoke/ssu, np.
↪array([guess, ]))[0]
    else:
        return fsolve(lambda ssu: nu - 0.0022*stoke*ssu + 1.35*stoke/ssu, np.
↪array([guess, ]))[0]
```

The kinematic viscosity is,

$$\nu = \frac{\mu}{\rho} = \frac{3.715 \, \frac{lbm}{ft\,hr}}{48.05 \, \frac{lbm}{ft^3}} = 2.148 \cdot 10^-5 \, \frac{ft^2}{s}$$

[4]:
```
kin_viscosity = mu/rho
ssu_viscosity = SSU(kin_viscosity)
ssu_viscosity
```

[4]:
```
34.11804944489399
```

Thus, the SSU value for viscosity is around 34. The flow rate across the main pump is 10.7 $\frac{ft^3}{s}$, which is 4800 gallons per minute. Figure 2 below shows the relationship and procedure for determining the correction factors.

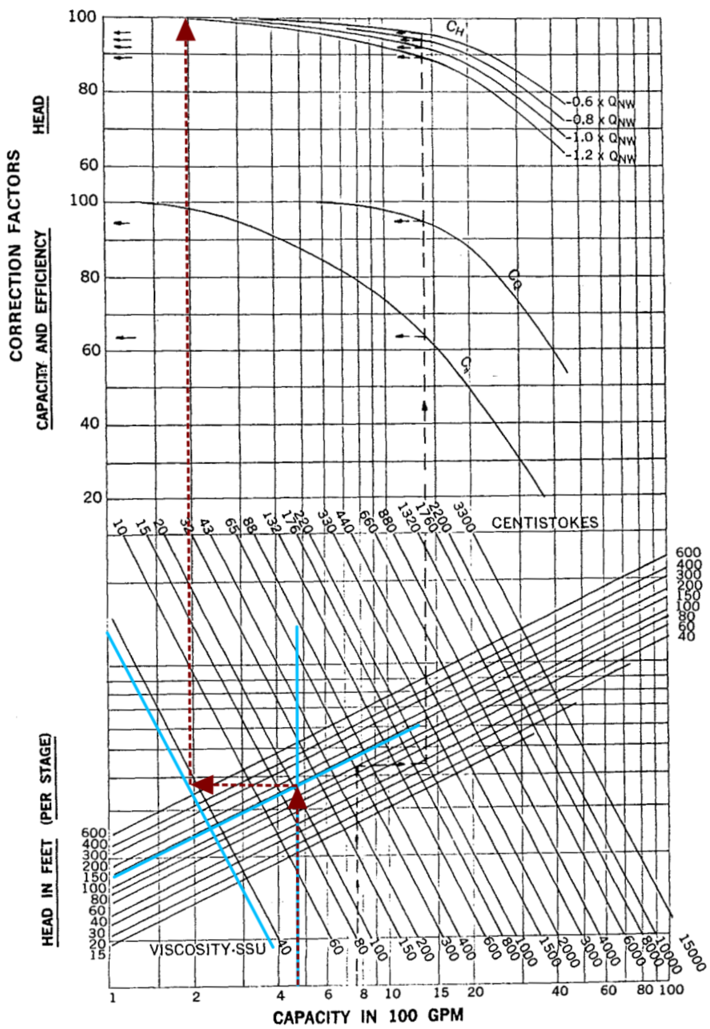


Figure 2: Correction Factors

The results show that the correction factors are close to 100% for the head, flow rate, and efficiency because the viscosity of water is low; therefore, **the viscous correction factors are negligible**.

3.2 Part B

Figure 3 below is a good starting point for determining which pump to select. With a head requirement of 145 ft and a flow rate of 4800 gallons per minute, the 8x10-17 is a starting point.

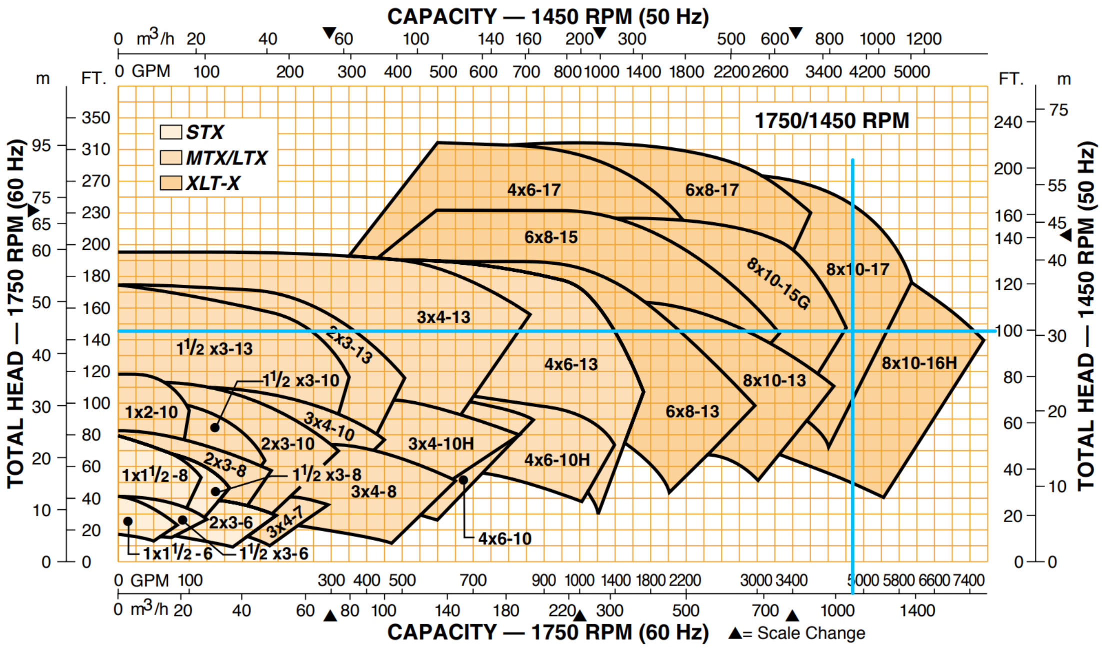


Figure 3: Model 3196 Pump Selections

Figure 4 below shows the breakdown of the 8x10-17 pump selection with the head and flow rate requirements shown.

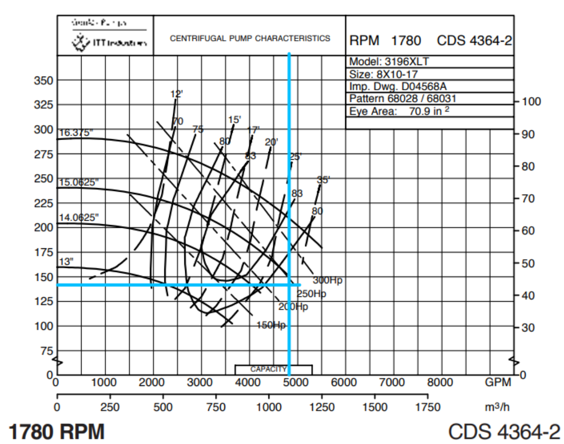


Figure 4: 8x10-17

While this certainly is a consideration, there is one other option to choose from. The 8x10-16H shown in Figure 5 should also be considered.

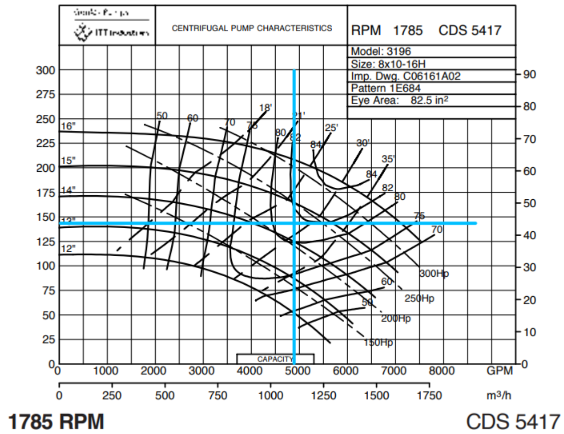


Figure 5: 8x10-16H

The choice between the two should be determined based on the efficiency of the pump. For the 8x10-17, the efficiency shown in Figure 4 is below 80%, but for the 8x10-16H, the efficiency is closer to 82%; therefore, the 8x10-16H will be selected as the main pump. The specifications of this selection are shown in Table 2.

Table 2: Goulds Pump Information

Specification	Value
Model Number	3196
Size	8x10-16H
Speed	1785 RPM
Rotor Diameter	15”

3.3 Part C

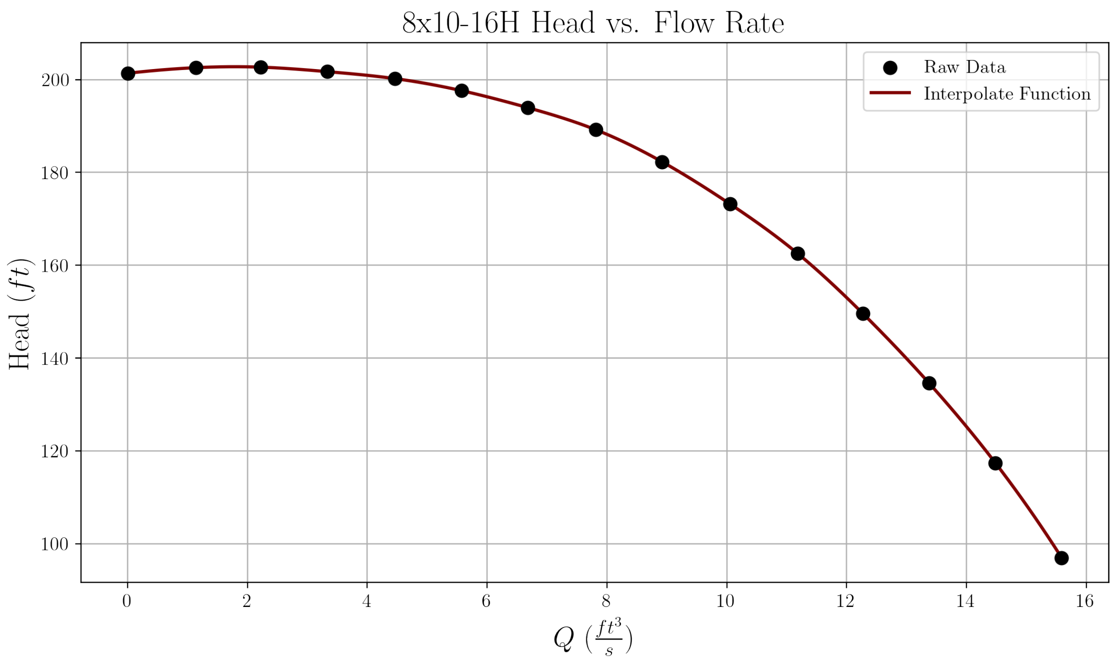
The graph of the head versus the flow rate may be acquired from Figure 5 using this tool, which is able to extract data from an image.

[5]:
```
flow_rates = np.array([3.531757334093072, 512.2795025159023, 998.8569258520843, 1496.4397607519227, 2005.0545903351372, 2502.557675875819, 3000.0075951770627, 3508.462926041963, 4005.753346624893, 4513.996012532041, 5022.158929080035, 5508.09835754296, 6004.990031330106, 6501.775372638374, 6998.40121522833])/(7.48052*60)  # ft^3/sec

heads = np.array([201.32412418114492, 202.52378239817713, 202.63657077755624, 201.67017943605805, 200.1654799202506, 197.57647393904867, 193.90572486471086, 189.15579606949584, 182.23981771575043, 173.16291654799198, 162.46340074052972, 149.59527200227853, 134.56622045001419, 117.37368271147818, 96.93591569353458])  # ft

Ws_lamb = interp1d(flow_rates, heads, kind='cubic', fill_value='extrapolate')
Q_values = np.linspace(0, flow_rates[-1], 1000)
```

```python
plt.scatter(flow_rates, heads, zorder=3, color='black', label='Raw Data')
plt.plot(Q_values, Ws_lamb(Q_values), label='Interpolate Function')
plt.xlabel(r'$Q$ ($\frac{ft^3}{s}$)')
plt.ylabel(r'Head ($ft$)')
plt.title('8x10-16H Head vs. Flow Rate')
plt.legend()
plt.show()
```



The flow rates may now be computed again, but this time, the head is a function of the flow rate. If the head values for the booster pumps remain, then the first loop equation is all that needs to be adjusted (just the W_s term).

[6]:
```python
def actual(x, b2, b4, b7, b10):
    Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q10, Q11 = x
    # all expressions need to be set to zero
    return [
        Q1 - Q2 - Q3,
        Q6 - Q2 - Q4,
        Q3 - Q4 - Q5,
        Q5 - Q10 - Q7,
        Q7 - Q8 - Q9,
        Q11 - Q6 - Q7,
        K1*Q2*abs(Q2) + p2.h(Q2) + p6.h(Q6) + p11.h(Q11) + p1.h(Q1) -
 ↪Ws_lamb(Q1) + 0.1*Q1*abs(Q1) - b2,
        p4.h(Q4) + K3*Q4*abs(Q4) - p2.h(Q2) - K1*Q2*abs(Q2) + p3.h(Q3) + b2 -
 ↪b4,
```

```python
        p7.h(Q7) + p8.h(Q8) + K4*Q8*abs(Q8) - p6.h(Q6) - p4.h(Q4) -␣
↪K3*Q4*abs(Q4) + p5.h(Q5) + b4 - b7,
        p9.h(Q9) + K4*Q9*abs(Q9) - p8.h(Q8) - K4*Q8*abs(Q8),
        p10.h(Q10) + K2*Q10*abs(Q10) - p11.h(Q11) - p9.h(Q9) - K4*Q9*abs(Q9) -␣
↪p7.h(Q7) + b7 - b10
    ]

actual_solution = fsolve(actual, Q_guess, args=(*b, ))
actual_solution
```

[6]:
```
array([11.15358038,  2.84791583,  8.30566455,  2.77622447,  5.52944008,
        5.6241403 ,  2.68007152,  1.34390004,  1.33617148,  2.84936856,
        8.30421182])
```

The actual flow rates and the required flow rates may be compared using the percent change method,

$$\% \; change = \frac{actual - original}{original} \cdot 100$$

[7]:
```python
(actual_solution - balanced_solution)/balanced_solution*100
```

[7]:
```
array([4.31180223, 4.97259406, 4.0871356 , 2.32109213, 4.99702085,
       3.6467848 , 5.00454977, 5.00488648, 5.0042111 , 4.98994025,
       4.08113143])
```

All the flow rates appear to be within 5% of the original, which is not excessive. What is important to take out of this is that all the flow rates are greater than the original, meaning this pump will be able to meet the minimum requirements.

The required power for the main line using the conservative flow rates just calculated is,

$$power = \frac{\rho Q W_s}{\eta}$$

where η may be taken to be 82%, which is the efficiency in Figure 5 along the 15" line.

[8]:
```python
eta = 0.82
power = (rho*actual_solution[0]*Ws_lamb(actual_solution[0])*32.174)/eta
power_hp = power/550
power_hp  # hp
```

[8]:
```
193.5092485914832
```

Thus, the power required to push the fluid at this flow rate is 194 hp.