A Spreadsheet Program for the Calculation of Piping Systems and the Selection of Pumps

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I. Introduction

An important topic taught in most energy related mechanical engineering courses, such as thermal design or HVAC, are piping system calculations coupled with the required pump calculations, so as to appropriately select a pump. To facilitate this instruction, an Excel workbook program, **Pump_Pipe.xls**, has been developed that will perform flow system calculations and pump selection analysis. The spreadsheet performs both the piping system calculations and the pump selection analysis. After a brief review of basic pump analysis and piping system analysis, this paper continues with a description of the spreadsheet. The spreadsheet is then demonstrated with a very simple flow system. Two design problems are then worked with the program. One problem deals with a large water system (part of the California State Water System), while the other problem looks at pump selection for automotive oil cooling system. Results of these problems show both the utility of the spreadsheet, as well as its shortcomings. The paper concludes with comments and recommendations.

II. Background

The basis for the pump analysis utilized in the spreadsheet is the use of the dimensionless pump parameters defined below:

Discharge Coefficient: $$C_Q = \frac{\dot{V}}{N\,D^3} \quad (1)$$

Head Coefficient: $$C_H = \frac{\Delta P}{\rho N^2\,D^2} \quad (2)$$

Isentropic Efficiency $$\eta_s = \frac{\dot{W}_{ideal}}{\dot{W}_{actual}} \quad (3)$$

where N is the pump speed and D is the pump rotor diameter.

It has been seen that by using these dimensionless groupings a single set of relationships may be developed for most axial flow pumps and a second set for most centrifugal pumps (see [1]). Shelby [2] has developed a set of operating equations for these two types of pumps, Axial Flow Pump: $C_H = 2.9253 - 4.3748C_Q + 6.548C_Q^2 - 5.0912C_Q^3$ (4)

$\eta_s = -0.019531 + 2.5351C_Q - 1.5606C_Q^2 - 0.43822C_Q^3$ (5)

Centrifugal Pump: $C_H = 5.7529 + 1.6748C_Q + 27.735C_Q^2 - 643.7C_Q^3$ (6)

$\eta_s = 0.022009 + 17.372C_Q - 95.082C_Q^2 + 113.59C_Q^3$ (7)

By having an mathematical relationship between flow rate and pressure boost, equivalent to the C_H equations provided above, the pump selection analysis can now be done analytically rather than with the traditional graphical approach.

For a piping system in which all of the components are aligned in series, the pressure drop is given by

$$(\Delta P)_{\text{system}} = \sum_{\text{components}} (\Delta P)_i + \rho g(\Delta z) \tag{8}$$

It proves convenient to break the component drop pressure term into three parts,

$$(\Delta P)_{\text{system}} = \sum_{\text{pipes}} (\Delta P)_i + \sum_{\text{valves/fittings}} (\Delta P)_i + \sum_{\text{contractions/expansions}} (\Delta P)_i + \rho g(\Delta z) \tag{9}$$

Now by introducing friction factors and loss coefficients we may rewrite this as

$$(\Delta P)_{\text{system}} = \frac{8\rho\dot{V}^2}{\pi^2}\left[\sum f_{p,i} + \sum f_{v/f,i} + \sum f_{c/e,i}\right] + \rho g(\Delta z) \tag{10}$$

where

$$f_{p,i} = \frac{f_i L_i}{D_i^5} \tag{11}$$

$$f_{v/f,i} = \frac{K_i}{D_i^4} \tag{12}$$

$$f_{c/e,i} = K_i\left[\frac{1}{D_{i,in}^2} - \frac{1}{D_{i,out}^2}\right]^2 \tag{13}$$

To properly select a pump for a given system, we desire

$$(\Delta P)_{pump} = (\Delta P)_{system} \tag{14}$$

By diving this equation by $\rho N^2 D^2$, we can write

$$(C_H)_{pump} = (C_H)_{system} \tag{15}$$

Our pump design is then governed by

$$(C_H)_{pump} = \frac{8}{\pi^2}\frac{\dot{V}^2}{N^2 D^2}\left[\Sigma f_{p,i} + \Sigma f_{v/f,i} + \Sigma f_{c/e,i}\right] + \frac{g(\Delta z)}{N^2 D^2} \tag{16}$$

where $(C_H)_{pump}$ will be given by one of the two cubic equations developed by Shelby and given above. Then the pump selection is accomplished by setting the speed (N) and pump rotor diameter (D) so as to satisfy the equation above and maximize the pump efficiency. By carrying this process out for both pump types, then observing which pump type has the most realistic speed and pump rotor diameter, a final pump selection may be made.

III. Description of Spreadsheet

The spreadsheet is divided into three sections. At the very top of the spreadsheet, shown in Figure 1, the user enters the volume flow rate, the density and kinematic viscosity of the working fluid, the piping roughness, and the net elevation change for the flow system. By specifying the roughness in this part of the spreadsheet, it is assumed that all piping elements will have the same roughness. As shown in Fig. 2, the next section performs the piping system calculations. The user specifies the piping, fittings and valves, and expansions and contractions that constitute the piping system. Only series flow systems may be considered. The template for the spreadsheet has seven entries for pipes and one entry each for various fittings and valves. A zero (0) entry for the length of a pipe section will eliminate that section from the calculations. A zero (0) entry for the diameter of a fitting or valve will eliminate that device from the calculations. A zero (0) entry for the large diameter of an expansion or contraction will eliminate that device from the calculations. If additional entries are needed, e.g. more than one 90 elbow or more than six pipe sections, the user must modify the spreadsheet to handle this situation. This modification includes inserting the necessary number of rows below the entry of interest and then dropping and dragging the needed cells. The pressure drop (DP on the spreadsheet) and the sum of the f-factors (S-F_{device} on the spreadsheet), defined in Eqns. (10)-(12), for each device grouping is calculated separately and provided at the bottom of the grouping. The overall pressure drop for the system, including any overall elevation changes, is provided in the pump selection section. Friction factors for piping

Figure 1. Top of **Pump_Pipe.xls** Spreadsheet

Vflow	Density	Kin Visc	Roughness	Elev.
(m^3/s)	(kg/m^3)	(m^2/s)	(m)	(m)
1.00E+00	998	9.61E-07	2.00E-04	0

Figure 2. Piping System Calculation of **Pump_Pipe.xls** Spreadsheet

Pipes and Tubes							
Pipe ID	Dia.	Length	Velocity	Re	f	Fpipe	
	(m)	(m)	(m/s)				
	1.83	0	0.38019635	724055.4	0.014031	0	
	2.54E-02	0	1973.52524	52166196	0.035019	0	
	2.54E-02	0	1973.52524	52166196	0.035019	0	
	2.54E-02	0	1973.52524	52166196	0.035019	0	
	2.54E-02	0	1973.52524	52166196	0.035019	0	
	5.08E-02	0	493.38131	26083098	0.028293	0	
	2.54E-02	0	1973.52524	52166196	0.013382	0	
					S-Fpipe	0	
					DP	0	Pa
Fittings and Valves							
Fitting ID	Dia	K	Ff/v				
	(m)						
Gate Valve(threaded)	0	0	0				
Gate Valve(flanged)	0	0	0				
Globe Valve(threaded)	0	0	0				
Globe Valve(flanged)	0	0	0				
90 Elbow (threaded)	0	0	0				
90 Elbow (flanged)	0	0	0				
180 Elbow (threaded)	0	0	0				
180 Elbow (flanged)	0	0	0				
		S-Ff/v	0				
		DP	0	Pa			
Contractions/Expansions							
C/E ID	Dlarge	Dsmall	K	Fc/e			
	(m)	(m)					
Sudden Expansion	0	0.0254	0	0			
Sudden Contraction	0	0.0254	0	0			
			S-Fc/e	0			
			DP	0	Pa		

Figure 3. Pump Calculations of **Pump_Pipe.xls** Spreadsheet

Flow System CH:	1.9803		Speed (rps)	Dia (m)	CQ
Total DP(kPa):	67.0805		30	0.1942	0.2276
	CH	D(CH)	Efficiency		
Axial	1.9813	0.001	0.471		
Centrifugal	-0.0153	1.008	0.390		

are calculated following Roberson and Krowe [1],

$$\text{Re} < 2100 \qquad f = \frac{64}{\text{Re}} \tag{15}$$

$$\text{Re} > 2100 \qquad f = \frac{0.25}{\left[\log\left(\frac{k/D}{3.7} + \frac{5.74}{\text{Re}^{0.9}}\right)\right]^2} \tag{16}$$

The loss coefficients are calculated from curve fits obtained from the data provided by White [3].

The lower section of the spreadsheet allows for selection of the appropriate pump for the specified flow system. The selection criteria is to match the head coefficient, C_H, for the flow system to that for the pump (after selecting a the pump type) by specifying the pump speed and pump rotor diameter. One way to approach this is to set the pump speed and then vary the pump rotor diameter until the difference between the two C_H's, called D(CH) on the spreadsheet, is negligible. The Solver tool in Excel may be used for this process. The pump speed is then changed and the process is repeated, so as to determine the pump speed and rotor diameter that will maximize the pump efficiency, while still satisfying the matching of the two C_H's. By doing this for both pump types a selection decision can be made based on efficiency and realizable values for the pump speed and pump rotor diameter.

To demonstrate the spreadsheet we consider the very simple flow system shown in Fig. 4 with additional details provided in Table 1. We wish to determine the most appropriate pump for water at 295 K flowing through this system with piping of galvanized steel at 25 gpm. The first step is utilizing **Pump_Pipe.xls** for this problem is to convert all parameters over to SI units. With this accomplished, the flow system can be entered into the spreadsheet. This section of the spreadsheet is shown in Fig. 5. The results of the pump selection analysis are given in Table 2. As one experienced with pipe selection might predict, one would choose the centrifugal pump with a rotor diameter of 7 cm and a speed of 45 rpm.

IV. Example Design Problems

Two design problems are provided that students can use to explore the pump selection design process.

California State Water System: The California State Water System calls for fresh water from northern California to be transported to the three major metropolitan areas of California: Los Angeles, San Francisco, and San Diego. One portion of the system calls for the water to be raised 1926 feet and transported 8.5 miles through 6 feet diameter concrete tunnels of roughness 0.8 mm. There are eight (8) 90° flanged elbows in this portion of the system. The annual flow of water though this portion is 6.5526×10^{11} gallons.

Figure 4. Example Flow System

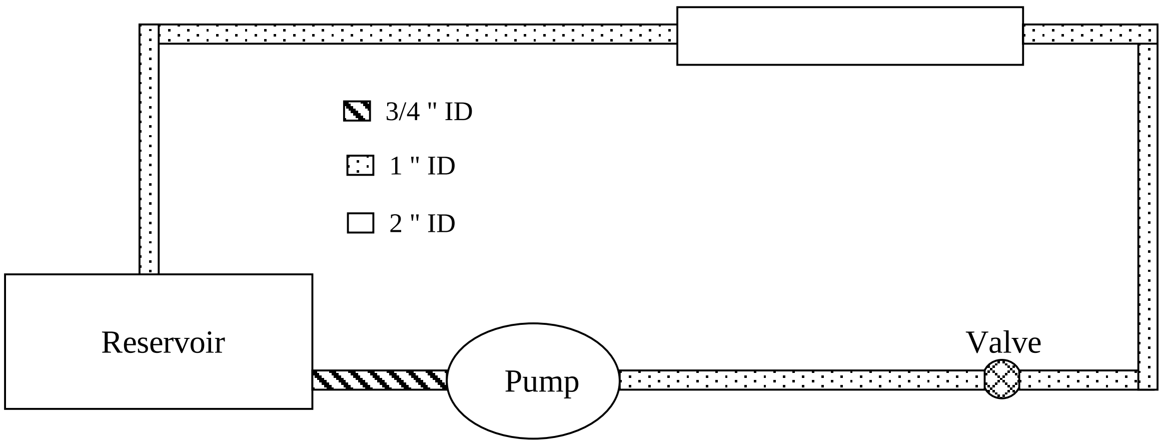

Table 1. Example Flow System Dimensions

Component	ID(inches)	length
Pipe	3/4	5"
Pump	--	--
Pipe	1"	1’
Gate Valve (fully open)	1"	--
Pipe	1"	1’
90° Elbow (threaded)	1"	--
Pipe	1"	3’
90° Elbow (threaded)	1"	--
Pipe	1"	6"
Expansion	1"-2"	--
Pipe	2"	1’
Contraction	2"-1"	--
Pipe	1"	1’
90° Elbow (threaded)	1"	--
Pipe	1"	2’

Figure 5. Pump_Pipe.xls Layout for Example Flow System

Piping System Calculations							
Vflow	Density	Kin Visc	Roughness	Elev.			
(m^3/s)	(kg/m^3)	(m^2/s)	(m)	(m)			
1.58E-03	998.00	9.61E-07	1.50E-04	0			
Pipes and Tubes							
Pipe ID	Dia.	Length	Velocity	Re	f	Fpipe	
	(m)	(m)	(m/s)				
	0.01905	0.127	5.54341312	109897	0.035891	1816808	
	0.0254	0.3048	3.11816988	82422.76	0.033255	958757.1	
	0.0254	0.3048	3.11816988	82422.76	0.033255	958757.1	
	0.0254	0.9144	3.11816988	82422.76	0.033255	2876271	
	0.0254	0.1524	3.11816988	82422.76	0.033255	479378.5	
	0.0508	0.3048	0.77954247	41211.38	0.029312	26408.79	
	0.0254	0.3048	3.11816988	82422.76	0.033255	958757.1	
	0.0254	0.6096	3.11816988	82422.76	0.108083	6232091	
					S-Fpipe	14307229	
					DP	28892.97	Pa
Fittings and Valves							
Fitting ID	Dia	K	Ff/v				
	(m)						
Gate Valve(threaded)	0.0254	0.22381	537705.676				
Gate Valve(flanged)	0	0	0				
Globe Valve(threaded)	0	0	0				
Globe Valve(flanged)	0	0	0				
90 Elbow (threaded)	0.0254	1.4106	3388980.06				
90 Elbow (threaded)	0.0254	1.4106	3388980.06				
90 Elbow (threaded)	0.0254	1.4106	3388980.06				
90 Elbow (flanged)	0	0	0				
180 Elbow (threaded)	0	0	0				
180 Elbow (flanged)	0	0	0				
		S-Ff/v	10704645.8				
		DP	21617.6757	Pa			
Contractions/Expansions							
C/E ID	Dlarge	Dsmall	K	Fc/e			
	(m)	(m)					
Sudden Expansion	0.0508	0.0254	0.75	1013559			
Sudden Contraction	0.0508	0.0254	0.315	425694.7			
			S-Fc/e	1439253			
			DP	2906.524	Pa		

Table 2. Results of Pump Selection Analysis for Example Flow System

Axial Flow Pump

Speed (rpm)	**Diameter (m)**	**Efficiency**
60	0.0754	0.130
90	0.0528	0.260
120	0.0417	0.386
180	0.0307	0.594
240	0.0252	0.730
300	0.0219	0.803
360	0.0198	0.836
420	0.0183	0.848
480	0.0171	0.848
540	0.0163	0.845
600	0.0155	0.839

Centrifugal Flow Pump

Speed (rpm)	**Diameter (m)**	**Efficiency**
30	0.1010	0.676
45	0.0694	0.929
60	0.0567	0.889
90	0.0459	0.723

Table 3. Results of Pump Selection Analysis for California Water System

Axial Flow Pump

Speed (rpm)	**Diameter (m)**	**Efficiency**
30	4.9	0.036
60	2.58	0.165
120	1.44	0.457
180	1.07	0.666
240	0.89	0.778
300	0.78	0.831
360	0.71	0.847
420	0.66	0.849
480	0.62	0.843

Centrifugal Flow Pump

Speed (rpm)	**Diameter (m)**	**Efficiency**
30	3.41	0.788
45	2.41	0.930
60	2.02	0.837
90	1.66	0.663

After entering the flow system on the spreadsheet, the pump selection analysis is then performed for both types of pumps. These results are shown in Table 3. Looking at these results, neither pump type seems a good choice. The most efficient axial flow pump operates at 420 rpm with a rotor diameter of 0.66 m. Though the rotor diameter is realistic the speed seems exceptional high for a pump this large. For the centrifugal pump, the highest efficiency requires a pump with rotor diameter of 2.41 m running at 45 rpm. Though the speed is acceptable the rotor diameter seems unrealistically large. With neither pump type being unacceptable, one would probably wish to explore the possibility of using multiple pumps in series or parallel. These possibilities could be explored further still using the **Pump_Pipe.xls** program.

Oil Cooler Pump: In high performance racing engines, it becomes necessary to cool the engine oil. A fin-tubed heat exchanger is used to maintain the oil at an appropriate operating temperature. In the heat exchanger the oil flows through five (5) 3/8 inch aluminum tubing (roughness of 0.0015 mm) each of length 15 inches. There are five (5) 180°, 3/8 inch elbows in the heat exchanger. The flow system from the oil pump to the heat exchanger consists of 12 inches of 3/8 inch diameter tubing and two 90°, 3/8 inch elbows. The flow system from the heat exchanger to the oil pump consists of a 3/8 inch to 3/4 inch sudden expansion, one 90°, 3/4 inch elbow, one 3/4 inch open gate valve, and 30 inches of 3/4 inch diameter tubing. The oil flow rate is 0.03 kg/s and its average temperature is 350 K. The results of the pump selection analysis for this problem are shown in Table 4. For this design problem the pump selection is much clearer. Certainly the decision would be to employ a centrifugal flow pump of rotor diameter 1.44 cm running at 120 rpm.

V. Conclusions and Recommendations

Pump_Pipe.xls allows student to quickly perform flow system analysis. Even though the pump selection is done for on-design conditions, the spreadsheet program does allow for the students to look at performance variations due to off design conditions. This would allow one to do some probabilistic design studies for flow systems. Some obvious shortcomings of the program include its inability to perform calculations for parallel flow systems, the somewhat limited types of valves and fittings built into the spreadsheet, and the constraint that all valves are fully open. Though creating a spreadsheet that could perform the iterative calculations required of parallel flow systems would be a considerable challenge, the other two shortcomings could quite easily be addressed. Both the spreadsheet and user's guide are available for access and download at the Thermal Engineering Computer Aided Design (TECAD) homepage in the Department of Mechanical Engineering at Michigan State University. The URL address is

http://www.egr.msu.edu/~somerton/TECAD.

The spreadsheet has been used with success in teaching a senior level elective course in thermal design (ME 416 Computer Assisted Design of Thermal Systems) at Michigan State University.

Bibliography

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Table 4. Results of Pump Selection Analysis for Oil Cooler System

Axial Flow Pump

Speed (rpm)	**Diameter (m)**	**Efficiency**
30	0.08	-0.0137
60	0.0404	0.002857
180	0.0141	0.1493
240	0.011	0.24
300	0.0091	0.335
360	0.0079	0.418
480	0.0063	0.578
600	0.0055	0.66
720	0.0048	0.758
840	0.0044	0.797
960	0.0041	0.838
1080	0.00381	0.842
1200	0.00362	0.848
1500	0.00324	0.842

Centrifugal Flow Pump

Speed (rpm)	**Diameter (m)**	**Efficiency**
30	0.056864	0.1288
60	0.02832	0.4085
120	0.0144	0.9168
180	0.0109	0.8693