Fluid Flow Systems Analysis
To Save Energy

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ABSTRACT

Industrial processes use rotating equipment (e.g.; pump, fan, blower, centrifugal compressor, positive displacement compressor) and pipe (or duct) to move fluid from point A to B, with many processes using electric motors as the prime mover.

Most of the systems in the industry are over-designed to meet a peak load demand which might occur over a small fraction of the time or to satisfy a higher pressure demanded by a much smaller user in the same process. The system over-design will result in a selection of larger but inefficient rotating equipment and electric motor system. Some of the typical design examples that result in higher energy usage are given below.

- A rotating equipment serving multiple end-users with varied process needs.
- Under-designed system components such as a smaller pipe diameter, a longer pipe run, and/or a smaller control valve taking excessive pressure drop.
- A multi-pass heat exchanger to obtain closer temperature approach and an exchanger with a smaller surface area to reduce the capital cost. The process, however, is penalized with a higher pressure drop and a higher annual operating cost.
- A routine practice in the process industry to design process control valves that consume as much as 30% of the system pressure drop or 10 psi minimum at normal fluid flow.
- A centrifugal pump or fan not operating on its best efficiency point (BEP) of the curve.

A careful life cycle cost and economic evaluation must be undertaken to ensure that the process audit, reengineering and equipment selections are not impacting the industrial process goals, but result in a least optimal cost over the life of the project.

The paper will define, discuss, and present various "process systems" in chemical, hydrocarbon and pulp & paper industries. It will discuss the interactive impact of the changes in the mechanical system configuration and the changes in the process variables to better redesign the system and reduce the cost of operation. It will also present a check list of energy conservation measures ("ECM") or opportunities. Such ECMs will be related to hydraulics, system components, process modifications, and system efficiency. Two or three case studies will be presented focusing on various conservation measures that improve electrical operating efficiency of a distillation column system. An incremental cost and payback analysis will be presented to assist the investment in process optimization and energy savings' measures.

Defining the Fluid Flow Systems

A typical fluid flow system consists of a *mechanical system* and a *process system.* A Process Flow Diagram (PFD) defines the heat and material balance for that fluid flow system, and a Piping and Instrumentation Diagram (P&ID) defines the mechanical and design configuration of the same system. For example, a mechanical system of a compressed air system may consist of various end-users of compressed air, delivery or distribution system (piping, valves, fittings, controls, etc.), compressor (centrifugal or positive displacement), its associated equipment (aftercooler, receiver, dryer, filter, etc.), and a driver (electric motor).

The process system will consist of air pressure and temperature at end-users, quantity and quality of air requirement, physical properties (molecular weight, polytropic exponent), ambient air temperature and air pressure, moisture in the suction air, etc. The energy consumption is impacted by the design of mechanical and process systems as well as the end-user load profile and hours of operation. It is very important to understand the technical equations used in the calculations of flow rate at various standard temperature and pressure (STP) options, inlet air density, outlet air density, compressor capacity, adiabatic or polytropic head, discharge temperature, break horsepower, and compression ratio. A further discussion of a recent article on compressed air can be found in Energy Engineering, (Volume 95, No. 6, 1998) and therefore, another case study from a petrochemical industry will be presented in the next section.

Design Practice and Baseline Model

A design engineering firm normally evaluates the three operating scenarios at best; namely, the normal flow, the maximum flow, and the turndown flow. The pipe, fittings, and pumps are selected using the maximum flow rate, but control valves are sized to operate under the all three flow conditions. This may result in control valve pressure drop at the normal flow rate to be as much as 30-40% of the system pressure drop or 10-15 psi minimum. The electric motor is usually a next larger size than the one estimated at maximum flow rate condition. In addition, a single pump is generally designed to serve many users. The sum of all load is the pump flow capacity. The total dynamic head of the pump is, however, controlled by one user which either requires a higher delivery pressure or is far away (such as tank farm) with an undersized pipe line and/or the user has a high static head requirement. In any case, that flow loop becomes the controlling head for the pump selection. A control valve in other circuits or loops will consume the additional pressure drop. An engineer can start preparing an off-line model of the system and develop a baseline or current operation model once the process boundaries are drawn and set points (related to pressure, flow, level or even fluid composition) are established. A spread sheet or a computer software program can assist in the baseline model development. The friction losses due to pipe, fittings, and valves are calculated. An estimation or field measurement of pressure drop in overhead condenser, heat exchanger, filter, etc. is made. Once the system model is verified, then various "what if" case studies are conducted. The goal is to develop an optimal model of a fluid flow system that meets the production targets as well as minimizes the energy usage under various operating scenarios. Most chemical plants and refineries operate 24 hours a day, 7 days a week, year around with minimum planned downtime. The following section outlines a case study problem statement for fluid flow systems analysis and its analysis of energy savings' options.

Case Study Problem Statement

A process engineer or an energy analyst is evaluating a distillation column that is separating binary mixture of benzene and toluene. The column, with an overhead pressure of 5 psig, produces a distillate containing 99 benzene and a bottoms product containing 95 weight percentage toluene. A Product/Reflux pump (P-101) is sized for 843 gpm at 280 ft of liquid head. Reflux flow is 2.54 times the distillate rate or 605 gpm. Benzene product flow to off site tanks is 200 gpm. A 38 gpm product flow is directed to another process unit. All process parameters and elevations are shown in the Figure 1.

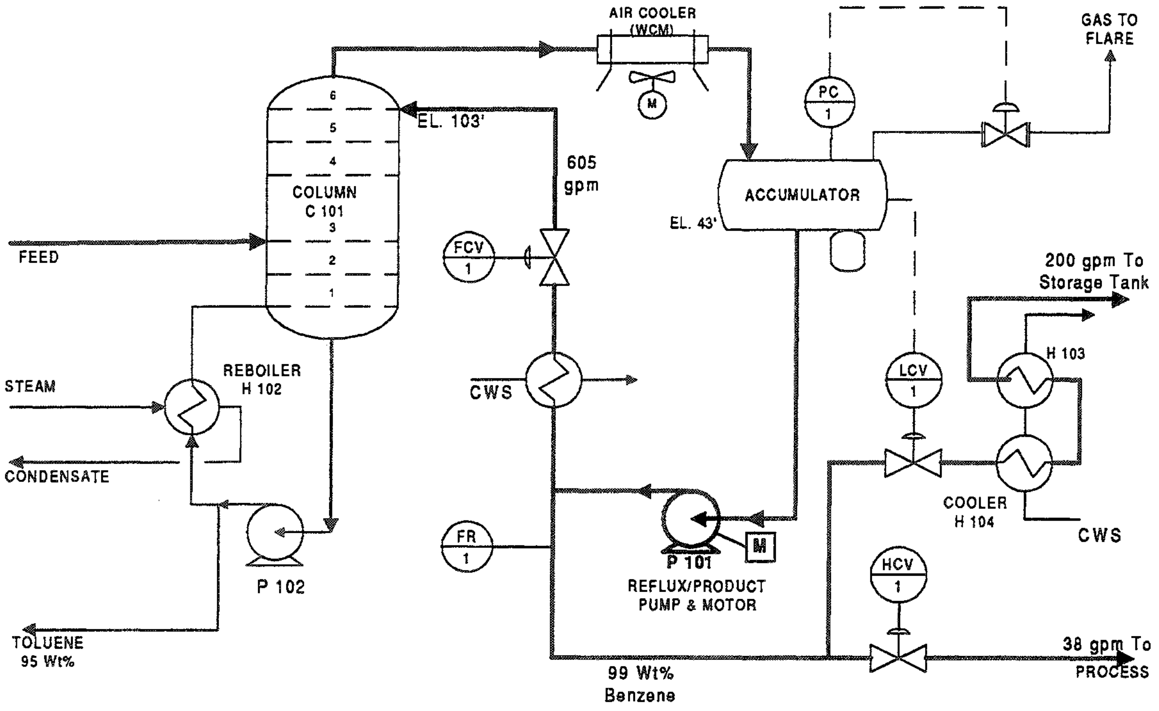


Figure 1. Base Case Operation & Design of Benzene/Toluene Distillation Column With a Single Pump

The pump P101 is designed for three delivery duties: Reflux flow, Product flow, and Process flow. The pump suction and discharge piping with fittings and valves are sized and laid out that followed generally acceptable good engineering practice. The flow system has three control valves. The reflux back to the tower is controlled by a flow control valve (FCV-1), product discharge flow to the storage tank is controlled by a level controller (LCV-1) from the accumulator and flow to another process unit is set by a hand control valve (HCV-1). There are other control strategies available but they are out of scope for this article. The system also has other equipment such as heat exchangers, air cooler, and tanks. The pump

P101 is a Goulds model 3x4-13 LTX, 3196 with a 75 hp electric motor. The certified pump curve information is available in the maintenance engineering file and is used in the analysis to plot systems curve and characteristic curves at different operating scenarios.

The following above grade physical elevations and the delivery pressures (Table 1) were noted on the P&IDs and verified in the field.

Table 1. Base Case Elevation and Delivery Pressure

	Elevation above Grade, Ft.	Delivery Pressure, psia
Reflux line to top of column	103	20.17
Pump centerline	3	124
Accumulator liquid level	43	NA
Storage tank normal level	23	15
Process unit	13	25

The goal is to evaluate and optimize the process design, and to reduce the energy usage. The analysis will create more than one case study. Each case study will have one or more changes in *Process System* as well as *Mechanical System.* Interactive effect of more than one ECM will have to be factored in the energy usage. For this analysis, we will assume that steady state flow requirements will not be changed. We will primarily focus on splitting the pump P-101 duty into two parallel pumps, one dedicated to reflux flow only and another pump for product and process discharge flow. We will also evaluate implementation of a variable frequency drive (VFD) replacing flow control valve, and re-plot the pump characteristic curve, system curve and estimate energy savings. Appropriate changes to the control valve pressure drop will be made to meet the process design requirements. Other ECMs can be larger pipe sizes, rerouting of lines to reduce length, but those changes can be expensive and may not result in good implementable projects. A check list of possible ECMs is presented in a later section.

Base Case Model

It is important to model the base case accurately to establish which flow circuit (end-user) out of three flow circuits controls the pump selection. The pump flow is sum of all three end-user flow requirement, but the pump head is determined from the worst case end-user demand, which, in this case is the reflux flow circuit from the Pump 101 back to the top of column. The flow control valve pressure drop at normal flow is 30 psi. The two other flow circuits will have the same pump discharge pressure, but the control valves (LCV-1 and HCV-1) will be sized to consume that additional head. At normal flow rates, the level control valve in the flow circuit to tank will have a pressure drop of 64 psi and the hand control valve in the flow circuit to another process unit will have a pressure drop of 94 psi.

The following Table 2 (Pump Calculation Sheet) provides the "controlling" base case operation and Table 3 lists the major hydraulic parameters of three base case flow circuits (reflux flow, storage tank flow, and process flow).

Table 2. Pump Calculation Sheet For the Base Case Operation

PROJECT :	Summer Paper	JOB NO :	ACEEE99
CLIENT :	ACEEE	PUMP NO :	P 101
LOCATION :	New York	CASE NO :	DESIGN CASE
SERVICE :	Benzene	PUMP MFR :	Goulds Pump
LIQUID PUMPED BENZENE		PREPARED BY :	Parekh

LIQUID PROPERTIES		UNITS	PUMP DIFFERENTIAL PRESSURE		UNITS
Pumping Temperature (PT)	°F	195	Discharge Pressure	psia	124.3
Viscosity @ PT	CStroke	0.3411885	Suction Pressure (+ for Lift)	psia	30.35
Vapor Pressure (VP) @ PT	psia	20.172809	TOTAL PUMP DIFF. PRESSURE	psi	93.95
Specific Gravity (SG) @ PT		0.8037008	TOTAL DYNAMIC HEAD	feet	270.04
Flow - Normal @ PT	gal/min	843	BHP and kW CALCULATION		
PUMP HEAD CALCULATION			Hydraulic Horsepower	Hp	46.2
SUCTION PRESSURE			Pump Efficiency @ C. O. P.	%	71.5
Original Pressure	psia	20.1728	BRAKE HORSEPOWER	bhp	64.62
+Static Head	feet	40	Electric Motor Efficiency @ C. O. P.	%	90
- Line Loss	feet	5	ASD Efficiency @ C. O. P.	%	100
- DP Equipment	psi	2	Electric Motor (Name Plate HP)	hp	75
PUMP SUCTION PRESSURE	psia	30.35	% Motor Loading	%	86.16
NET POSITIVE SUCTION HEAD			ELECTRIC POWER USE	kW	53.56
Static Head	feet	40	ENERGY & DEMAND CALCULATION		
- Line Loss	feet	5	Operating Hours	hr/yr	8760
+[(Original Pressure - VP)]	psia	0.00	Electricity Use	kWh/yr	469195.58
AVAILABLE NPSH (LIQUID PUMPED)	feet	29.25	Demand Use	kW/yr	53.56
PUMP REQ'D NPSH (WATER)	feet	26	Energy Charges	$/kWh	0.08
DISCHARGE PRESSURE			Demand Charges	$/kW/mo	5
Delivery Pressure	psia	20.1728	TOTAL ENERGY COST	$/yr	40749.31
Static Head	feet	100			
Line Friction Loss	feet	69.9553			
Total Equipment Pressure Drop	psi	45	FORMULA :		
HEAT EXCHANGER	psi	10	PSI = Ft x SG x 0.433		
ORIFICE	psi	5	HHP = GPM x DIFF. PRESS. /1715		
FLOW CONTROL VALVE	psi	30	bhp = hhp / Pump Efficiency		
PUMP DISCHARGE PRESSURE	psia	124.3	kW = bhp x .7457 / (Motor Efficiency x ASD Efficiency)		

Table 3. Hydraulic Parameters of Base Case Single Pump Service

		Reflux Circuit 1	Product Circuit 2	Process Circuit 3
Pump Flow - Normal @ PT		843	843	843
Circuit Flow - Normal @ PT	gpm	605	200	38
PUMP SUCTION PRESSURE	psia	30.35	30.35	30.35
DISCHARGE PRESSURE				
Delivery Pressure	psia	20.1728	15	25
Static Head	feet	100	20	10
Line Friction Loss	feet	69.9	43.5	6.64
Total Equipment Pressure Drop	psi	**45**	**87.5**	**94**
Heat Exchanger 1	psi	10	10	NA
Heat Exchanger 2	psi	NA	15	NA
Orifice	psi	5	NA	NA
Control Valve	psi	**30**	**62.5**	**94**
PUMP DISCHARGE PRESSURE	psia	124.3	124.3	124.3
Total Pump Diff. Pressure	psi	93.95	93.95	93.95
Total Dynamic Head	feet	270.04	270.04	270.04
Pump Efficiency	%	71.5	71.5	71.5
Break Horsepower	bhp	64.62	64.62	64.62
ENERGY USE (Annual)	kWh	469,195	469,195	469,195

Systems Analysis To Save Energy

It is important to understand and model the existing operation using either a spread sheet or a computer software program specifically designed for the fluid flow systems analysis. This should be followed by the analysis of one or many processes and mechanical component variables to evaluate the impact on power usage by these changes. A brief check list of energy conservation measures is given below that can be applied to pump, fan, blower, and compressor systems. We will evaluate some of the measures in the following sections.

Pressure Drop

- Reduce piping system pressure loss by increasing the line size and rerouting the pipes.
- Optimize process equipment pressure loss in the flow lines.
- Reduce or eliminate control valve pressure loss.

System Efficiency

- Operate rotating equipment at or close to its best efficiency point.
- Split a single system into more than one to achieve higher aggregate O&M efficiency.
- Downsize the pump (or trim impeller or modify compressor wheels) and motors. This is only an end-result of the system improvement or optimization.
- Modify a process control scheme, including loading/unloading and spillback controls on positive displacement compressors, and location of throttling control.
- Install variable frequency drives (VFD) - investigate needs and implications carefully. The variable frequency drive is not always the best solution!
- Improve the operating efficiency by implementing an energy recovery strategy. For example, recover heat of compression to heat a building or replace a low pressure steam heating.
- Replace the standard efficiency motors by the premium efficiency motors.

Process Modifications

- Lower the delivery pressure (without impacting process requirement) at user(s).
- Lower the pressure profile of the system.
- Incorporate an advanced process control scheme and algorithm to eliminate operator intervention.
- Reroute or resequence the process streams.
- Reduce the compressor inlet temperature.
- Regenerate or replace catalyst (same for in-line filters) to eliminate an excessive pressure drops due to carbon build-up.
- Reduce or eliminate the minimum flow by-pass recirculation flow.

Energy Conservation Measures

We will investigate three ECMs in detail and evaluate their impact on energy savings. Please note that there will be many other measures (singular or combination) that can be investigated. The goal, however, must be to pick the most cost effective measures for analysis. These measures will have a greater chance for implementation. The following measures are analyzed further.

1. ECM 1: Divide the pump P-101 hydraulic duty into two separate pumps operating in parallel.
2. ECM 2: After implementing the ECM 1, investigate a variable speed drive to replace the flow control valve in the reflux line.
3. ECM 3: Increase the reflux line size from 4" to 5". This ECM 3 is inclusive of the ECM 1 and ECM 2.

Two Pumps in Parallel (ECM 1)

The following Figure 2 shows how the benzene/toluene distillation system will be served by two pumps. All other mechanical and process parameters will remain the same as the base case.

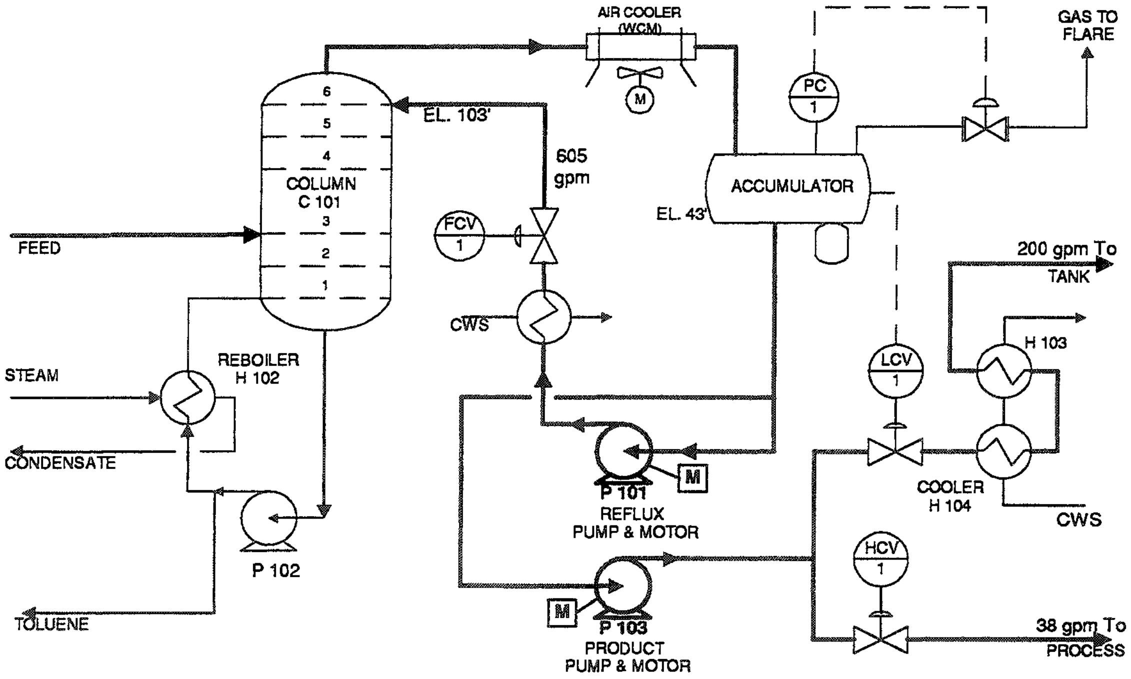


Figure 2. Two Pumps in Parallel

The Table 4 on the next page summarizes the key variables of the base case and ECM 1 case, and estimates a 13.6% energy saving. The energy saving is due to a reduced pressure drop in LCV-1 and HCV-1 control valves. The alternate pump P-101 is a Goulds model 3196 MTX, size 3x4-10 process pump. It has a slightly better mechanical efficiency (72.8%) than the base case pump. The new product pump (P-103) has a 63% pump efficiency at the normal flow rate of 238 gpm at 135 ft of head. In all case studies, a 90% electrical motor efficiency is used. It should be noted that upgrading a standard efficiency motor to premium efficiency motor would only gain 2-4% in operating efficiency. However, upgrading and selecting a right pump would significantly increase the operating efficiency by as much as 5 to 10%. An energy engineer should focus on fluid flow systems components (e.g., motor, pump, VFD, pipe, control valves, etc.) that could improve system efficiency dramatically while keeping the cost down.

The controlling hydraulic case for the pump P-103 is product flow to the storage tank via two coolers in the series. As you will notice, an additional electrical energy saving can be achieved by reconfiguring two coolers from series to parallel operation (eliminates 10 psi pressure loss) and increasing the line size to the storage tank (reduces~6 psi).

Table 4. Hydraulic Parameters of Two Pumps in Parallel (ECM 1)

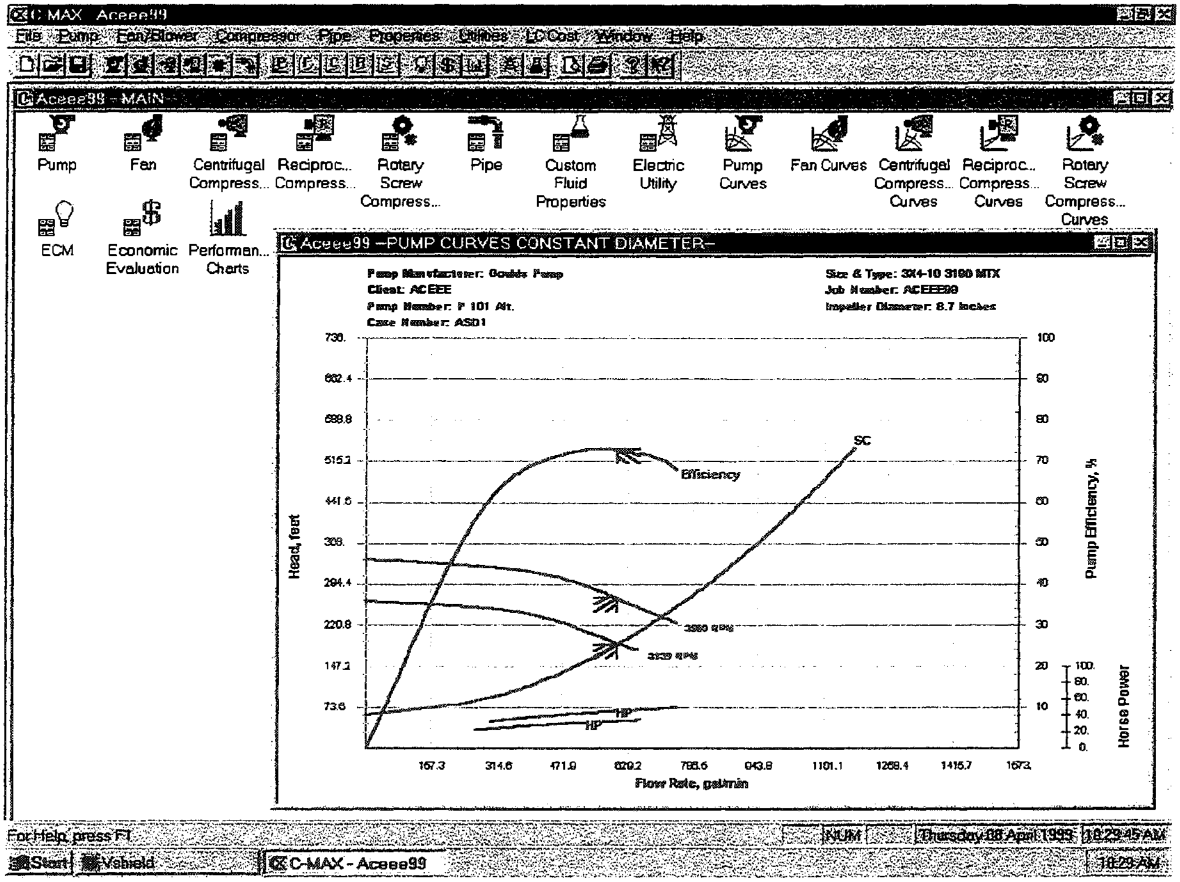
		Base Case	Split Pump ECM 1	
			Reflux	Product
Pump Flow - Normal @ PT		843	605	238
Circuit Flow - Normal @ PT	gpm	843	605	238
PUMP SUCTION PRESSURE	psia	30.35	30.35	30.35
DISCHARGE PRESSURE				
Delivery Pressure	psia	20.1728	20.1728	15
Static Head	feet	100	100	20
Line Friction Loss	feet	69.9	69.9	43.5
Total Equipment Pressure Drop	psi	**45**	**45**	**40**
Heat Exchanger 1	psi	10	10	10
Heat Exchanger 2	psi	NA	NA	15
Orifice	psi	5	5	NA
Control Valve	psi	**30**	**30**	**15**
PUMP DISCHARGE PRESSURE	psia	124.3	124.3	77.11
Total Pump Diff. Pressure	psi	93.95	93.95	46.76
Total Dynamic Head	feet	270.04	270.04	134.39
Pump Efficiency	%	71.5	72.8	63
Break Horsepower	bhp	64.62	45.55	10.3
ENERGY USE (Annual)	kWh	469,195	330,706	74,816
Energy Savings Over Base Case	kWh			63,673
Percent Energy Savings	%			**13.57%**

A variable speed drive for the reflux flow (ECM 2)

It is assumed that the control system response time permits a replacement of the current flow control valve by a variable speed drive. The VFD will control the reflux flow that is either set by column overhead temperature, pressure or composition. During the normal operation, the system will see the reduction in system pressure profile equivalent to control valve pressure drop (30 psi). Figure 3 plots system curve and pumps curves at normal speed as well as at variable speed.

It should be noted that during turndown and reduced reflux flow rates, the savings will be even greater with a VFD. For example, at reduced reflux ratio of 2.0 (versus base case of 2.65), the reflux flow will decrease to 476 gpm. This will result in reduced discharge pipe frictional losses to 43.31 feet from 69.9 feet ($\Delta P \propto flow^2$). The flow control valve will pinch close to absorb the additional pipe pressure loss and higher head generated by the pump curve at the lower flow. In this specific case, the system gains discharge line friction loss of 26.59 feet (=69.9-43.31), the exchanger frictional loss drops from 10 psi to 6.19 psi, and the orifice pressure drop is now 3.1 psi from base case 5 psi. The pump head (without a VFD) would be

99.56 psi or 286.15 feet of liquid. The flow control valve, FCV-1, now has a pressure drop of 52 psi, an increase of 22 psi over the base case operation. A VFD, with a 96% efficiency, would save 15.62 kW or 49% savings over the case if no VFD was used but only the reflux flow was reduced from 605 gpm to 476 gpm. This case is not further presented due to space limitations.



Pump Manufacturer: Goulds Pump
Client: ACEEE
Pump Number: P 101 Alt.
Case Number: ASD1

Size & Type: 3X4-10 3196 MTX
Job Number: ACEEE99
Impeller Diameter: 8.7 Inches

Figure 3. Pump Curves and System Curves (ECM 2) Using C-MAX software

Increase Reflux line size to 5" (ECM 3)

The base case pipe friction losses from pump P 101 to the top of the column is 69.9 feet. The discharge pipe consists of two 4" diameter schedule 40 pipe segments with a 120 feet straight length & number of fittings. The friction losses are calculated using "non-compressible flow Benoulli's equation (Reference: Crane TP 410 manual & C-MAX software). At normal benzene flow of 605 gpm, the 4" Φ pipe has a fluid velocity of 15 feet per second. Increasing this pipe to 5" Φ schedule 40 pipe would decrease the velocity to 9.70 fps and reduce the frictional losses to 19.8 ft, saving additional energy. The Table 5 tabulates the hydraulic and energy savings parameters for ECM 2 and ECM 3.

Table 5. Hydraulic and Energy Savings Parameters for ECM 2 and ECM 3

		Base	ECM 1 & 2		ECM 1, 2, & 3	
		Case	Reflux	Product	Reflux	Product
Pump Flow - Normal @ PT		843	605	238	605	238
Circuit Flow - Normal @ PT	gpm	843	605	238	605	238
PUMP SUCTION PRESSURE	psia	30.35	30.35	30.35	30.35	30.35
DISCHARGE PRESSURE						
Delivery Pressure	psia	20.1728	20.1728	15	20.1728	15
Static Head	feet	100	100	20	100	20
Line Friction Loss	feet	69.9	69.9	43.5	**19.8**	43.5
Total Equipment Pressure Drop	psi	**45**	**15**	**40**	**15**	**40**
Heat Exchanger 1	psi	10	10	10	10	10
Heat Exchanger 2	psi	NA	NA	15	NA	15
Orifice	psi	5	5	NA	5	NA
Control Valve	psi	**30**	**1**	**15**	**1**	**15**
PUMP DISCHARGE PRESSURE	psia	124.3	95.31	77.11	77.86	77.11
Total Pump Diff. Pressure	psi	93.95	64.96	46.76	47.51	46.76
Total Dynamic Head	feet	270.04	186.7	134.39	136.55	134.39
Pump Efficiency	%	71.5	72.8	63	72.8	63
Break Horsepower	bhp	64.62	31.49	10.3	23.03	10.3
ENERGY USE (Annual)	kWh	469,195	245,035	74,816	178,738	74,816
Energy Savings Over Base Case	kWh			149,344		215,641
Percent Energy Savings	%			**31.83%**		**45.96%**

The Table 6 summarizes the energy savings realized by conducting a systems analysis of the fluid flow system. An incremental cost and payback analysis in the Table 7 clearly indicate the attractiveness of these ECMs. An electricity cost of 8 cents/kWh and a demand charge of $ 5/kW/month are used in the calculations.

Table 6. Summary of Energy Savings

Base Case Energy Use (Single Pump)	kWh/yr	**469,195**			
Energy Savings Contribution		**Incremental Savings**		**Cumulative Savings**	
		Measure	**%**		**%**
ECM 1 Two Pumps	kWh/yr	63,673	13.57%	63,673	13.57%
ECM 2 VFD on Reflux Pump	kWh/yr	85,671	18.26%	149,344	31.83%
ECM 3 Larger Discharge Pipe	kWh/yr	66,297	14.13%	215,641	45.96%
Total of ECM 1, 2, & 3	kWh/yr	**215,641**	**45.96%**		

Table 7. Cost Estimate and Payback Analysis

		One Pump	Two Pumps in parallel	Two Pumps & a VFD	2 Pumps, a VFD & 5" Pipe
Pump	3x4-13 MTX, 3196	$10,000			
Goulds	3x4-10 MTX, 3196		$9,000	$9,000	$9,000
	1 1/2x3-13 MTX, 3196		$8,000	$8,000	$8,000
Motor	75 hp	$3,695			
GE	50 hp		$2,187	$2,187	$2,187
	15 hp		$710	$710	$710
VFD	460 volts,50 hp			$4,925	$4,925
GE	In line Reactor			$570	$570
FCV-1 in Reflux Line				-$2,915	-$2,915
Larger CS Pipe (5") Incremental Cost Only					$1,500
TOTAL		$13,695	$19,897	$22,477	$23,977
Incremental Equipment Cost			$6,202	$8,782	$10,282
Installation L&M Cost (50%)			$3,101	$4,391	$5,141
TOTAL Incremental Cost Increase			$9,303	$13,173	$15,423
Cumulative Energy Savings		kWh/year	63,673	149,344	215,641
Cumulative Cost Savings			$5,481	$12,972	$18,730
Simple Payback			1.70	1.02	0.82

Recommendations

The continuous reengineering and process optimization are necessary as industrial outputs change to meet the market demand. A company that implements an aggressive plant energy management and demand side management program will reap the benefit of operating cost saving, which always flows to the bottom of the income statement. A penny saved in NOT equal to a penny earned!! For commercial businesses, a penny saved is equal to 20 pennies earned (revenue) because the net income approximates to 5% of the revenue. The investment payback for efficiency improvement and savings projects could be justified on the basis of revenue that need not be earned to stay in business rather than on the basis of return on investment (ROI) of 2-3 years for the new capital projects. The bottom line to evaluate energy savings opportunities that should result in improved deployment of current and future capital investment.

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