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TIME-BASED MODELING OF SHIP BALLASTING FOR INCREASED PERFORMANCE

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ABSTRACT

Ship ballasting and de-ballasting are critical to a ship’s stability, and a major part of ship and port operations. Here, we examine the current procedures and potential issues that can arise when a quick turnaround in port is required. Through time-based modeling of the ship’s systems, new methods were used to analyze the feasibility of each scenario as well as ensure the systems were operating optimally. After rigorous testing, a new approach was developed to decrease time in port, increase system reliability/safety, and improve overall efficiency.

INTRODUCTION

Ship ballasting operations help to maintain the stability of the ship during loading and unloading and are an integral part of port activities. On large vessels, much of the process is remotely controlled and automated, and hand turned valves have been replaced by pneumatic and hydraulic controllers. The older level control systems have been replaced by onboard SCADA systems which gives the operator complete knowledge and control of where the tank levels are at, which parts of the system are operating, and includes and easy to read diagram.

Shipboard officers often become experts at ship operation, however there are many nuances to pumping and piping systems that take years to master. These systems are often looked at component by component. As such, when a bilge or ballast pump breaks down, it is blamed on the quality of the build. In reality, these systems are tied together and a problem pump or component may be tied to another part of the system. Even the Hydraulic Institute which is comprised largely of pump manufacturers now advocates a system based approach towards designing, maintaining, and optimizing their pumping systems (1). Each pump has a specific pump curve which shows the flow rates it will deliver at a certain head or pressure. However, where the pump operates on this curve is entirely defined by the system it is operating in and may have a significant effect on the process timing and reliability.

Time based hydraulic analysis of ship ballasting can be used to understand the piping network onboard, decrease the total time of the operation, and increase the reliability and efficiency of the included pumps and process equipment. The original challenge for this paper came in the form of a cooperative effort to keep a ship on schedule. The results provide insight on how slight changes in procedures may have dramatic effects on the outcome of the process. The hydraulic analysis additionally provides a visual to better understand the performance differences between options when value based engineering decisions are necessary.

While there are numerous types and setups for ballasting systems, the following methodology can be applied to any system. The ultimate key is to understand the hydraulic performance and how the interactions occur.

The initial challenge for this paper was to determine an optimized method of pumping out six ballast tanks on a ship while the ship's cargo was being loaded. The ship was required to complete the deballasting operation within 12 hours to meet a tight schedule. The ship had been unable to meet the schedule and experienced cavitation of the ballast pump as the tank levels dropped. The ballast system was initially modeled in a steady state to determine performance characteristics, and calculated the steady state balanced flow rates and pressures throughout the system. Subsequently multiple iterations and scenarios were run over a 12-hour time frame to determine operational time frames and feasibility.

Figure 1 shows the configuration of the ballast system as modeled. Each ballast tank, three on the port side and three on the starboard side, start out with a liquid level of 55 ft of sea

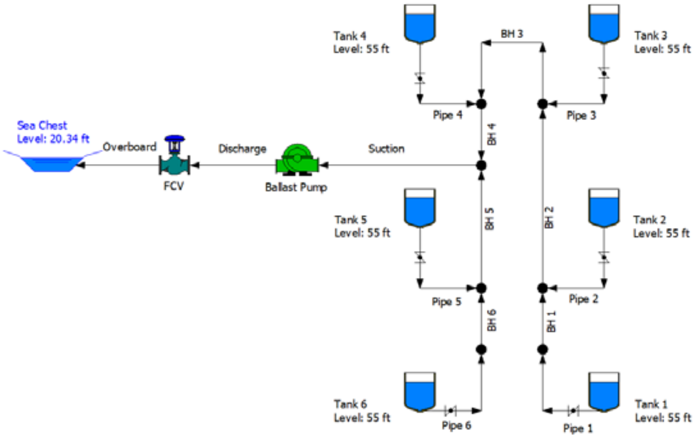

Figure 1. SHIP DEBALLASTING SYSTEM

water. A Ballast Pump and flow control valve (FCV) regulate the rate of discharge from the ballast tanks to the Sea Chest. The valves and fittings (elbows, T's, and pipe reducers) are also included in the model but are not shown in Figure 1.

NPSHa AND CAVITATION

One issue that must be addressed is as the tank levels decrease, the Net Positive Suction Head Available (NPSHa) also decreases. In addition, the NPSH required by the pump increases at higher flow rates, as shown on the NPSHr graph of the pump curve in Figure 2. Additionally, an increase in flow rate also increases the head loss in the suction piping, resulting in a reduction of the NPSHa.

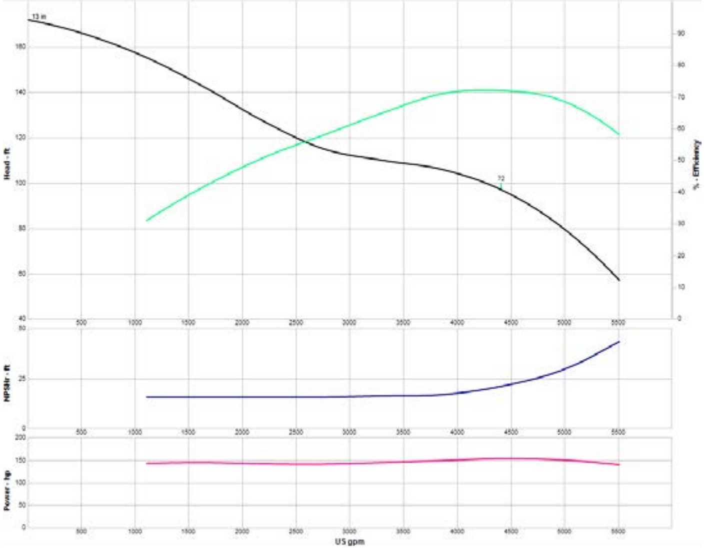

Figure 2. PUMP CURVE FOR BALLAST PUMP

To prevent cavitation from occurring, the ship must maintain an NPSH margin ratio (=NPSHa/NPSHr) of 1.3 during the entire operation. This essentially acts as a safety factor against unknowns. There are many factors which may change after initial design and installation of a system. For example, over time systems may experience a restriction in flow due to fouling, sediment build up, or many other factors. In addition, to minimize maintenance problems with the ballast pump and ensure the system is operating efficiently from an energy standpoint, the shipyard wants the Ballast Pump to remain within a Preferred Operating Region (POR) of 80% to 120% of the BEP flow rate at all times. It is well known in the pump industry that the reliability of the pump and mean time between failure is the greatest when the pump is operating at its best efficiency point. It is therefore highly desirable from both an energy efficiency standpoint, as well as a reliability standpoint, to run the pump in its ideal operating range. These limitations were input into the simulation to generate warnings if the flow rate or NPSHa fall outside of the limits.

ASYMMETRICAL DESIGN

Another issue that added to the complexity of the cavitation problem is the physical location of the Ballast Pump in relation to the tanks. The Ballast Pump is located between the #4 and #5 Ballast Tanks, so the overall system is not symmetrical. In other words, when the pump is lined up to the #4 Ballast Tank, there is less head loss in the suction piping than there would be when it is lined up to the #1 Ballast Tank. This means that the pump will have less NPSHa and therefore be more susceptible to cavitation when pulling out of the #1 Ballast Tank.

The asymmetric design also means that when two or more tanks are pumped down together, the tank levels will come down at different rates until equilibrium is reached between the driving head in each cross-connected tank and the pump suction. Once this equilibrium is reached, the flow rate from each tank will equalize and the tank levels will drop at the same rate. Figures 3 and 4 show the flow rate trend from each tank along with the tank levels when all six tanks are lined up to the Ballast Pump at the same time. Even though the tank levels are equal at the beginning of the simulation, the flow rates from each tank are different, causing a separation in the tank level trend.

EVALUATING THE CURRENT PROCEDURE

The first thing to be determined is how the system is operating under the current deballasting procedure used by the ship's crew. The procedure starts by pulling the water out of three tanks at the same time to a level of about 6.5 feet. Next, those tanks are isolated and the other three tanks are pumped down to 6.5 feet. Finally, the six ballast tanks are individually pumped down to a minimum level of about 0.5 feet.

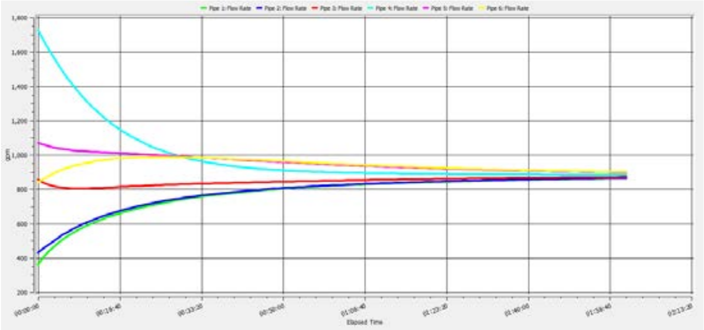

FIGURE 3. TANK FLOW RATES WITH ALL TANKS CROSS CONNECTED

Initially, the crew starts out with the FCV fully open to obtain the highest flow rate from the pump. When cavitation noises are heard as the tank levels drop, the flow rate is reduced until the noise subsides. Using this procedure, the crew is able to complete the deballasting operation in 13 to 15 hours, putting the ship behind schedule.

When this scenario was defined in the hydraulic simulation software and calculated until all tanks were empty, the tank level trend graph in Figure 4 was developed. The #4, #5, and #6 Ballast Tanks took almost five hours to pump down to 6.5 feet. Due to similar resistances in the piping system the trend for the #5 Tank is underneath the trend for the #6 Tank and may be difficult to distinguish. It took another five hours to pump the #1, #2, and #3 Ballast Tanks to the 6.5-foot level. It then took about 25 minutes to pump down each tank to 0.5 feet, adding another 2-1/2 hours to the procedure for a total time of about 12-1/2 hours. If additional time is added to account for valve manipulations, it is easy to see how even an operator who was on top of the situation would take 13 hours to complete the deballasting operation. If the operator had other tasks to complete and could not give his full attention to the procedure, even more time would be required, placing the ship further behind schedule.

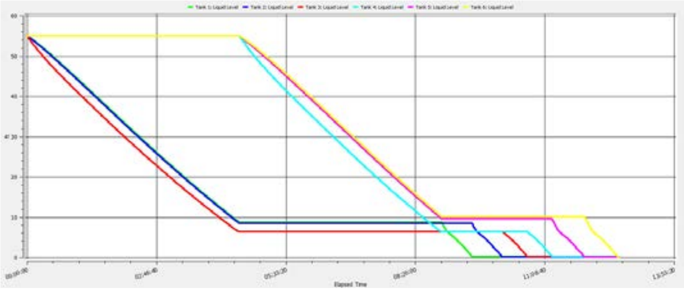

FIGURE 4. TANK LEVEL TRENDS WITH CURRENT PROCEDURE

PUMP CAVITATION AND COST

Cavitation, or the boiling of fluid in pumps, is another major concern in the pumping procedure. Its presence can demolish pumps rapidly. If there is a low intake pressure, or the pump is operating at the far end of its curve, it pulls the fluid through so rapidly that the fluid pressure drops below its vapor pressure. When this occurs, there is no longer sufficient pressure on the fluid to keep it in a purely liquid state.

Water boils at different temperatures depending on pressure. For example, at sea level water boils at 212°F, whereas, at the top of Mount Everest where the pressure is much lower, it boils at 160°F. In a pump, the pressure may drop low enough that water “boils” at 60°F, or whatever the ambient temperature may be. It may seem difficult for air to strip away steel in a pump, but it’s the millions of vapor bubble explosions and implosions that do the damage. This effect is clear once the pump is in operation. Cavitation can sound like gravel being pumped no matter the base fluid.

How does this tie in to pump selection and operation? Some users try to avoid pump challenges by spending extra money on an oversized pump. However, this may cost more money in terms of maintenance and repairs as the operating point could be far from the BEP.

The state of individual process piping is generally unknown and engineers tend to oversize pumps in an attempt to build in a margin of safety. In addition, a contractor may route pipes differently and add a safety factor into their calculations. This safety factor, however, generally goes on top of the worst-case design scenario. Engineering firms are incentivized by the fact that they do not want to be blamed for an undersized pump that cannot meet process requirements. Imagine the outrage if clients did not receive adequate water pressure from a shower, cooling from the HVAC, or flow from the waste system.

The general rule of thumb for safety factors is 10%. However, a junior engineer will generally assume a certain amount of required energy based on the expected piping, process, and control elements and 10% will be added to their calculation. A senior engineer may then review this work and add an additional 10%, just in case. Things can continue to become even more complicated as end users may introduce unrealistic expectations for production capacity or may want the infrastructure being put in place as part of a potential expansion project that is still years down the road.

When the pump is finally ordered, the manufacturer's representative will help select one that is large enough to handle these operations and then some. These safety factors end up compounding on each other and the actual process inherits something totally different than that which was originally required. This may leave the end user saddled with an inefficient pump and the possibility of hundreds of thousands of dollars in additional energy usage and maintenance work. Using software to model expected flow conditions at various operating points is recommended as a safeguard against such excesses.

Pumping System Optimization (2) from the Hydraulic Institute covers an evaluation of 1690 pumps at 20 process plants. The study discovered some alarming results. It found average pumping efficiency to be below 40% and that over 10% of pumps were less than 10% efficient. A major reason behind such poor numbers was improper pump selection.

These findings should be appreciated in the context of pump economics. The general rule is that a pump and motor combo will cost about $1 per day per horsepower of the motor at current land based energy costs of around $0.10 per kWh. While energy costs vary by location, they are generally significantly higher on maritime vessels. Therefore, this is a good starting point to begin understanding the potential costs being faced. For larger horsepower pumps running inefficiently, the wasted capital can be staggering and energy costs alone are seldom cause for change. Once the pumps are installed and running, the energy costs are out of sight, buried in the total fuel costs of the vessel, where propulsion may take center stage. Discovering the true cost of the pump is hard when it is buried amongst a myriad of other costs for running the equipment.

Evaluate The Options: Determine the System Line Up and Flow Rates

The ship wanted to evaluate other procedures to determine if the system could physically meet the time requirement of 12 hours. They came up with two feasible options:

A. Pump down all tanks together to some pre-determined level, then pull each tank down to 0.5 feet individually.

B. Pump down all tanks to 0.5 feet together, isolating each tank as it reaches its minimum level.

For both scenarios, the first thing to determine is the maximum flow rate at the start of the procedure when the ballast tanks are full. Using the POR, the maximum allowable flow rate through the pump would be 120% of BEP flow (4407 gpm), or 5288 gpm. Therefore, the FCV is initially set to 5285 gpm.

For either option, at some point as the tank levels and NPSHa decrease, the NPSH margin ratio will drop below 1.3 and place the pump in jeopardy of cavitation. At this point, the flow rate will have to be dropped to reduce the head loss in the pump suction piping and increase the NPSHa, and therefore the NPSH margin ratio. The level at which the NPSH margin is first exceeded is determined to be between 23 and 25 feet by running the simulation with a flow rate of 5285 gpm and making note of when the NPSH margin ratio warning is given. This occurs at the end of the tank level trend shown in Figure 3 above.

When the flow rate needs to be adjusted, what flow rate should we control to? As the tank levels continuously drop, the NPSHa will continuously drop as well. For every one-foot drop in tank level, there is a one-foot drop in NPSHa. If the system is automated sufficiently to allow a cascade control scheme, the set point of the flow control valve could receive a remote set point from the output of a tank level controller. In essence, this would be a NPSHa controller.

In the absence of such a sophisticated control scheme, we must determine the necessary flow rates at each tank level that will satisfy our NPSH margin requirement. The model is calculated with the tank levels at different intervals and the flow rate adjusted at each level to determine at what point the pump will have sufficient NPSHa. Table 1 below shows the flow rate set points needed to ensure sufficient NPSH is available based on tank levels. The #4 Ballast Tank level is used as the trigger for changing the flow rate since it is the closest to the Ballast Pump and its level will come down the fastest.

Option A: All Tanks to 4 Feet, Then Individually to 0.5 Feet

In this option, the ballast tanks are pumped down until #4 Ballast Tanks reaches a level of 4 feet, then the other five tanks are isolated and the #4 Tank is pumped down to 0.5 feet, at which point that tank is isolated and another one pumped down to the minimum level. The process is repeated to pump down each tank individually to 0.5 feet. The flow rate when pumping down each tank is set to the minimum flow of 80% of BEP flow, or 3525 gpm.

Tank 4 Level (ft)	FCV Set Point (gpm)
55 to 24	5285
24 to 20	5190
20 to 16	5070
16 to 12	4930
12 to 8	4755
8 to 4	4525
4 to 0.5	3525

Table 1. FCV SET POINTS FOR OPTION A

The tank level trend in Figure 5 is obtained when this scenario is defined in Overtime and the simulation ran. The deballasting operation using Option A takes just over 12 hours to complete, so initially this looks like a good option. However, since each tank is being pulled down individually to 0.5 feet, the entire flow rate of 3525 gpm is being drawn out of one tank at a time. This results in very high fluid velocities and head losses in the suction piping from the tank to the pump, causing the NPSH margin ratio limit to be exceeded while emptying the #3, #5, and #6 Ballast Tanks (the margin ratio drops as low as 1.12). While pumping down the #2 Ballast Tank the NPSHa drops to 15.8 feet, and to 14.6 feet while pumping down #1 Ballast Tank. Since these values are below the 16.6 feet of NPSH required, the pump will be cavitating for about 15 minutes near the end of the procedure.

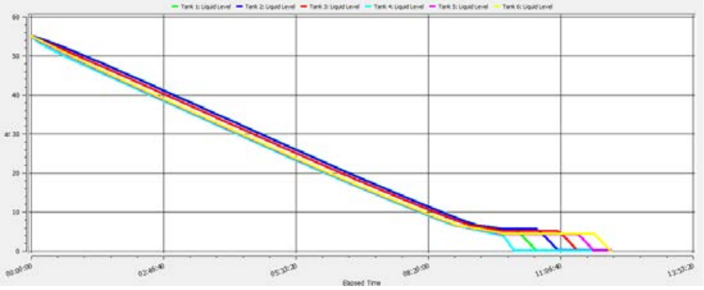

Figure 5. TANK LEVELS TRENDS FOR OPTION A

Option B: Pull All Tanks Down Together to the Minimum Level, Then Isolate Each Tank at 0.5 Feet

For this scenario, all six ballast tanks are pumped out together. As the tank levels drop and NPSHa decreases, the flow rate is adjusted to ensure the NPSH margin ratio is satisfied. The flow rate values in Table 2 are used, showing the maximum preferred flow rate from the pump for the first five and a half hours. Then the flow rate is adjusted downward in 100 gpm increments until the closest Tank #4 is emptied causing NPSHa to drop rapidly a the 11:41 mark. Since the pump is pulling out of multiple tanks, the flow rate from each tank will be lower than it would be if the pump was pulling out of one tank. This allows the overall flow rate to be higher when pumping out of multiple tanks at the same time. The flow rates in Table 2 below show when the FCV needs to be adjusted to ensure the NPSH margin is maintained. While there are more changes to the flow rates in Option B, these changes do not start for the first 5:30 and are only made once or twice and hour after that making it operationally feasible.

FCV (gpm)	Time (hr:min)	Tank 1 (ft)	Tank 4 (ft)	NPSHa (ft)	NPSHr (ft)
5285	0:00	55.00	55	79.76	37.75
5200	5:30	26.29	23.51	48.99	35.48
5100	6:04	23.21	20.49	46.02	32.82
5000	6:44	19.65	17.02	42.59	30.15
4900	7:25	16.06	13.52	39.15	28.19
4800	7:56	13.39	10.94	36.61	26.77
4700	8:19	11.45	9.08	34.79	25.36
4600	8:43	9.46	7.17	32.93	23.94
4500	9:18	6.77	5.42	31.11	22.52
4400	10:06	5.25	3.41	29.28	21.15
4300	10:50	3.63	1.53	27.47	20.38
4200	11:14	2.56	0.56	26.49	19.62
3250	11:41	0.33	0.55	16.61	16.34

Table 1. HYDRAULIC DATA FOR OPTION B

Conclusion

Oftentimes small changes may have dramatic effects on the overall performance of piping systems. By understanding the hydraulics of a system, optimizations are oftentimes achievable with little or no cost. Here by simply making several changes to an existing procedure, approximately an hour was cut off of the potential turn around time due to deballasting issues. By keeping the pumps operation within the preferred operating range, the life of the pump is increased and less maintenance will be required. The lack of cavitation will also add to the life of the pump and decrease costs.

The shipyard was able to prove that the current system could attain the goal of deballasting the ship within the 12-hour time frame without costly modifications. In addition, specific guidance could be provided to the ship's crew on how to change the operating procedure, along with the flow rate set points necessary to keep the Ballast Pump operating efficiently and to prevent cavitation as the tank levels dropped.

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