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Improving the Performance of a Chiller System during Operation

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Abstract

This research paper describes a case study of the model and design-based water chiller system that is more efficient during operation. The design was modeled using heat flow through the system and the varying parameters that impacts the chiller system such as evaporator, condenser and compressor were investigated for optimal performance of the system. The relevant thermal analysis and hydraulic analysis were performed separately for the tube-side and for the shell-side and solid works was used to design a chiller system that is more efficient during operation. The result shows that the optimized system is more efficient during operation. The suspended solids in the settlers ranges between 5 and 10 taken measured in different times of the day such as day, afternoon night shift. It was observed that the rate in which suspended solids flow in the system depends on the strength (adhesive) of the flocculent gel including the mass flow. It was also shown that the pH level was also improved in the system, and it ranged between the 9 & 9.5. That reduced the alkaline content of water and therefore scaling and slit built up will take place at a very low rate over the time. The results also revealed that there are variations with regards to the pH level and contributing factors were fluctuating mass flow rate and (b) process temperature variance.

Keywords: Chiller, optimize, performance, design and efficient.

INTRODUCTION

In South Africa buildings contributes to around 50% and 34% of the total consumption in energy and that is like the United States [1]. In most developed countries such as the United States, Russia and UK, chillers represent around 35% of the total commercial building HVAC cooling system and energy consumption [1-3]. It therefore important to optimize the performance and functionality of the chiller system to improve on energy consumption. From engineering perspective, it is possible to increase the energy efficiency in the chiller system by optimizing the system control parameters and this will involve several input variables, that impacts the load in the building and room temperature. This can also be done by developing a rule-based control method during operation. This method is more complex as it requires an exhaustive research investigation and a large variables of modelling and empirical simulations data needed to generate a set of optimal control parameters with varying input parameters and variables for optimal performance.

Some researchers like Hydeman and Zhuo [1-4] focused on developing a regression function using random parameters and performed varying simulation and tested the optimal speed of the of condenser water pumps and performance of the cooling tower fans during operation. Other research such as Yu and Chan [1-4] suggested a similar approach of using a condenser water loop control system for water cooled chillers during operation. The research was achieved through empirical simulations modelling and the optimization of key control parameters or variables such as the speeds of the condenser of the system water pump and the cooling tower fan during operation. The system was very sensitive to the room temperature and atmospheric weather condition during operation. Advanced approach of studying the flow rate of the chilled water in the system and the system condenser water was done with both parameters being studies as independent variables in the system during operation.

The main draw back in this study was the inability to study the flow rates in the system during operation which was addressed by [1-4] who solved this problem by studying the system flow rate as a function of the pressure difference in the system during operation. The performance of the evaporator is most affected by the pressure different in the cooling system during operation. The cooling function is controlled by the total amount of refrigerant passing through the cooler and the temperature level at which the refrigerant enters. Increased flow of refrigerant will remove more heat form the chilled water. In addition, since the pressure within the cooler will deterNampak the boiling point of the refrigerant, any restrictions in the vapor line leading from the cooler to the suction of the compressor will increase the refrigerant pressure within the cooler and consequently increase the boiling point. However, the heat required to boil the refrigerant is taken from the chilled water, a decreased flow of chilled water will decrease the boiling action of the refrigerant and in effect, reduce refrigerant flow and cooling capacity within the cooler during operation.

There are several conditions of flow and temperature, which will vary the total refrigerating effect of the system. Every cooler has a design pressure-temperature relationship and that any deviation from this relationship is the result of some malfunction or maintenance problem within the system. For instance, should the tubes of the cooler become fouled, the heat transfer will be decreased across the tubes. When this happens, a lower refrigerant boiling temperature will be required to remove the same amount of heat form the chilled water. This kind of condition can be deterNampakd by an analysis of the operator's logs showing the pressures and temperatures within the cooler over a long span of time. However, the performance of the chiller system greatly depends on the transient pattern of the controlled system of temperature and pressure during operation. If the design chiller system cannot respond to any change of control variable of pressure and temperature, it may lead to long searching time and this will impact the performance of the system. However, the relationship between the parameters or variables that impacts optimization frequency and energy saving modes are not well understood and this is mainly due to the lack of sufficient quantitative empirical analysis in research findings. To solve this problem, it is important to design a water chiller layout with improve mass flow of water in the system and study the varying parameters for optimal performance of the system during operation.

METHODOLOGY

The principle on which the refrigeration cycle is based is that the boiling/evaporating point of a liquid is dependent on the pressure to which the liquid is exposed to. For example, at atmospheric conditions (101.3 kPa) water will boil at 100°C, whereas at a lower pressure, the water will boil at a much lower temperature. This property is true for all liquids. By using this principal and an appropriate refrigerant, the pressure can be reduced to a point that the boiling point will be below that of the space which is to be refrigerated. This will mean that the heat energy from the environment will be absorbed by the refrigerant. The refrigerant can then be compressed to a pressure where the boiling point will be greater than the atmospheric temperature to where the heat can be rejected. This cycle can be seen in Figure 1 where the evaporator is situated between points 1 and 2, where the low-pressure refrigerant enters in its liquid state. At the pressure in which the refrigerant enters the evaporator, the corresponding boiling point will be lower than the temperature of the cold medium. Heat will then be transferred from the cold medium to the refrigerant, resulting in the liquid refrigerant boiling and forming a low-pressure vapor.

The vapor then enters the compressor (between points 2 and 3), where work gets done on the vapor to increase the pressure. Under ideal conditions, the vapors would not gain any energy and this would be an isentropic process. The high pressure, high temperature vapor will now enter the condenser (between points 3 and 4) at a pressure that results in the corresponding boiling point being greater than the temperature of the warm medium to which the heat will be transferred. As the heat is rejected from the vapor, it will result in the vapor refrigerant condensing into a liquid. The final process in the refrigeration cycle is as the refrigerant enters the expansion device (in this case the turbine between points 4 and 1), where the pressure can drop to the relevant pressure in the evaporator. From this point the process can now repeat itself. During the cycle that has been described above, all that has happened is that the heat energy that was present in the cold medium (in a mining application this will be the chilled water that is to be sent) has been absorbed from the cold medium and rejected into a heat sink (this would be the warm water in the condenser cooling towers which ultimately rejects the heat to the atmosphere). The cycle that has been described above is known as the Carnot Cycle and is the simplest of the cycles. The coefficient of performance (COP) of this cycle is simply calculated from the temperature limits between which the plant operates as is given as

$$COP_R = \frac{T_L}{T_H - T_L} \quad [1]$$

Where T_L is the liquid refrigerant temperature in the evaporator and T_H is the liquid refrigerant temperature in the condenser. In an actual refrigeration cycle, it is impractical to operate in the conditions in which the Carnot Cycle operates. For example, the compressive stage in the Carnot Cycle is entirely within the saturated vapor dome, and a compressor is unable to compress a liquid/gas mixture. Hence, in a practical situation the refrigerant that leaves the

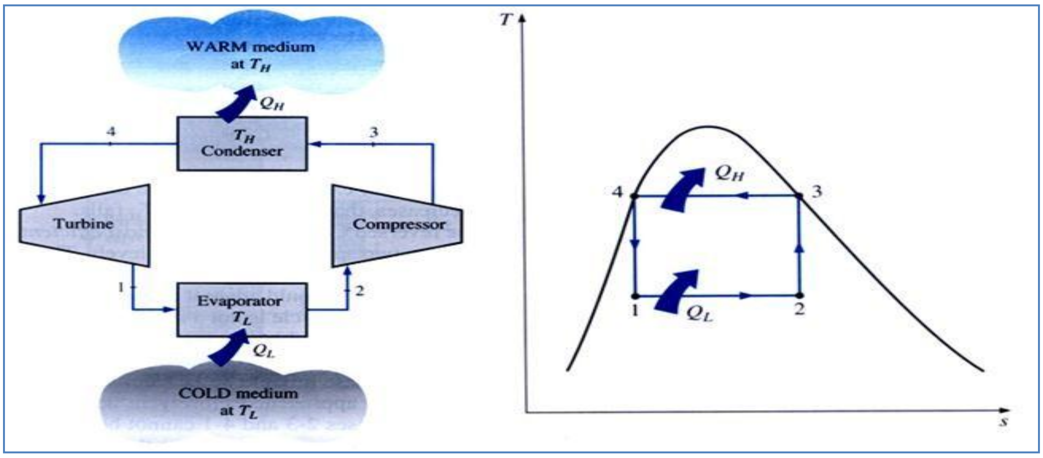

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Figure 1: An Ideal/ Carnot Refrigeration Cycle

evaporator will be in a gas phase for the compressor to be able to compress the refrigerant. In an ideal world, the refrigerant would be taken precisely to the point where it is a saturated vapor, but in real circumstances it is impossible to get the refrigerant exactly to that point and hence the refrigerant will be slightly super-heated before entering the compressor to ensure that no liquid refrigerant enters the compressor. In most refrigeration plants it is also not cost effective to use a turbine to decrease the pressure between the condenser and the evaporator and hence an expansion valve is used which results in an increase in the entropy of the refrigerant. The compression stage is also not an isentropic process in the real world, so the refrigerant will in fact entropy decreases with a decrease in temperature, which is actually advantageous as the specific volume of the gas is decreased, resulting in the compressor needing to do less work. There are also pressure losses which occur in the condenser and evaporator as is seen by the sloping lines between points 2' and 4 and points 7 and 8 as shown in Fig. 2. The pressure loss is however not usually a significant one when compared to the pressure differences across the compression and expansion stages. It is also quite difficult to get the refrigerant to be exactly on the saturated liquid line and hence the refrigerant is slightly sub cooled in the condenser to ensure that all the refrigerant is in the liquid phase before entering the expansion valve. This can be seen in Figure 2 between points 4 and 5.

The main purpose of the refrigeration cycle is to transfer heat from one source to another source. A refrigerant is used to absorb the heat from the source that need to be cooled, it then transfers this heat to another source which dissipate the heat into the atmosphere. In the process of transferring the heat from the refrigerant, the refrigerant cools down and start a new cycle to absorb heat again. Figure 3 shows a typical refrigeration cycle.

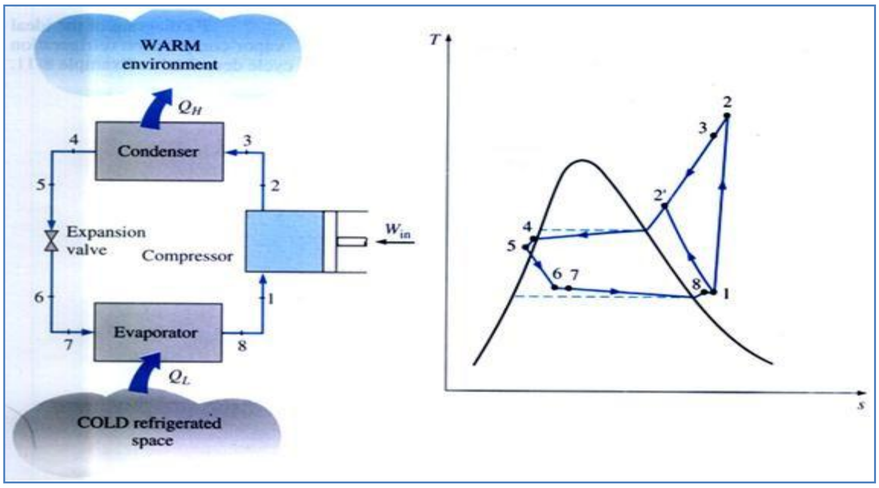

Figure 2: Actual Refrigeration Cycle

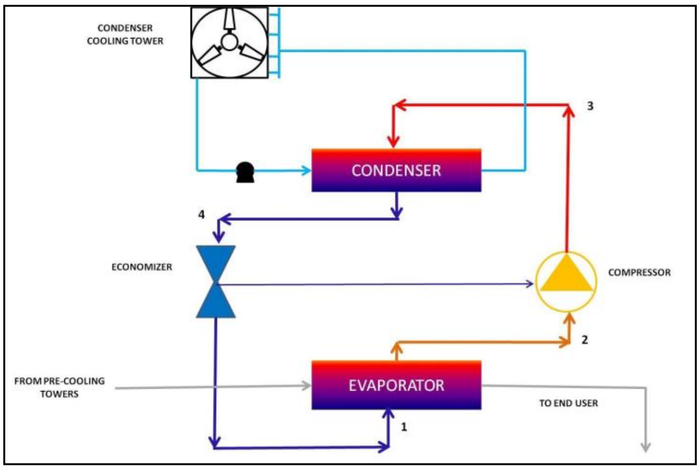

Figure 3: Refrigeration Cycle

At point number 1 in the figure above the refrigerant is at a low pressure and low temperature, approximately 200kPa and 2̊C, but this may differ from one machine to another. Water that needs to be cooled to be used for cooling purposes exchanges its heat with the cold liquid refrigerant. The refrigerant evaporates as it gains heat. Although the refrigerant gains heat its temperature stay constant as it changes state (latent heat transfer). The temperature of the refrigerant does not change but its state does. The heat absorbed by the refrigerant, called the refrigeration effect, can be calculated as as,

$$RE = \dot{m}\, refrigerant \cdot (h2 - h1) \quad [2]$$

where RE is the refrigeration effect calculated in Watt, $\dot{m}_{refrigerant}$ is the mass flow rate of the refrigerant in kg/s. h_2 is the enthalpy of the refrigerant at the exit of the evaporator in kJ/kg. h_1 is the enthalpy of the refrigerant when it enters the evaporator in kJ/kg. The heat absorbed by the refrigerant should be equal to the heat that the water loses at it passes through the evaporator. The heat given off by the water in the evaporator is given as

$$Q_E = mc\Delta T = m(T_{In} - T_{Out}) \quad [3]$$

Where Q_E is the heat extracted by the refrigerant from the water in the evaporator (W), m is the water mass flow through the evaporator (l/s), c is the specific heat of water (kJ.kg^{-1}K^{-1}), T_{in} is the temperature of the water entering the evaporator (K) and T_{out} is the temperature of the water leaving the evaporator (K). The saturated vapors refrigerant then leaves the evaporator and enters the compressor where it is compressed to a high pressure, superheated vapor. Again, the heat gained by the refrigerant can be calculated by calculating the difference in enthalpy between the inlet enthalpy and outlet enthalpy of the refrigerant in and out of the compressor given as,

$$WComp = \dot{m}\, refrigerant \cdot (h3 - h2) \quad [4]$$

Where W_{Comp} is the work done by the compressor (Watt), h_2 is the enthalpy of the refrigerant entering the compressor (kJ.kg^{-1}), h_3 is the enthalpy of the refrigerant after having left the compressor (kJ.kg^{-1}), $\dot{}_{refrigerant}$ is the mass flow of the refrigerant through the compressor in kg/s. To calculate the compressor work in this way is not always practical, because a real system is not as simple. In a real refrigeration system flash gas from the economizer is drawn into the second stage of the compressor. The flash gas come into the compressor at different enthalpy and the mass flow rate changes between the first and second stage of the compressor. Because of the difficulty in determining the enthalpy and the mass flow rate of the refrigerant not always being available, this calculation is impractical and there are easier ways of determining the work done by the compressor. The work done by the compressor can be calculated by using the amps drawn by the compressor motor given as

$$Wcomp = \sqrt{3} \cdot V \cdot A \cdot \eta motor \cdot \eta gearbox \cdot pf \quad [5]$$

Where W_{comp} is the work done by the compressor (Watt), V is the voltage of the electric supply to the motor (V), A is the amps drawn by the motor, η_{motor} is the motor efficiency (0.96), $\eta_{gearbox}$ is the gearbox efficiency (0.99), pf is the power factor of the electric supply (0.96). The superheated, high pressure refrigerant enters the condenser. In the condenser the superheated refrigerant exchanges heat with water from the condenser cooling towers. The water gains heat which it will give off to the atmosphere in the condenser cooling towers. The refrigerant gives off its heat to the water. It loses its superheat and then start changing state. The heat given off by the refrigerant can be calculated by using the difference between the enthalpy of the refrigerant at exit and entrance to the condenser is given as,

$$Qcond = \dot{m}\, refrigerant \cdot (h4 - h3) \quad [6]$$

where Q_{cond} is the heat dissipated from the refrigerant calculated in Watt, $\dot{m}_{refrigerant}$ is the mass flow rate of the refrigerant in kg/s, h_4 is the enthalpy of the refrigerant at the exit of the condenser in kJ/kg, h_3 is the enthalpy of the refrigerant when it enters the condenser in kJ/kg. The heat dissipated by the refrigerant as calculated above should be exactly equal to the heat gained by the water and is known as the condenser duty. In practical it is much easier to calculate the condenser duty by looking at the water side of the condenser. The condenser duty can then be calculated as

$$Q_C = mc\Delta T = m(T_{In} - T_{Out}) \quad [7]$$

where Q_C is the heat extracted by the water from the refrigerant in the condenser (W), m is the water mass flow through the condenser (l/s), c is the specific heat of water (kJ.kg^{-1}K^{-1}), T_{in} is the temperature of the water entering the condenser (K), and T_{out} is the temperature of the water leaving the condenser. (K). After calculating the evaporator duty, condenser duty and the work done by the compressor, a heat balance need to be obtained, (1st law of thermodynamics). The heat balance is calculated as,

$$HB = \frac{Q_{cond}}{Q_{evap} + W_{comp}} \quad [8]$$

where HB is a factor which is an indication if your heat balance is correct, Q_{cond} is the condenser duty (Watt), Q_{evap} is the evaporator duty (Watt), W_{comp} is the work done by the compressor (Watt). The heat balance needs to be equal to unity or 100%, which means that energy have not been created nor destroyed but just transferred from one place to another. If this is not within 2% of unity you may have made a calculation error or there are some issues with the instrumentation as the correct measurements are not achieved. The actual COP in the system can be computed as,

$$COP_{actual} = \frac{RE}{W_{comp}} \quad [9]$$

Where, RE is the refrigeration effect or evaporator duty and W_{comp} is the work performed by the compressor. The actual COP is a measure of how much of the electrical power put into the compressor motor is converted to cooling power. The power to cooling ratio is the inverse of the actual COP.

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The cycle efficiency is calculated by dividing the actual COP by the Carnot COP as given as,

$$\eta_{cycle} = \frac{COP_{actual}}{COP_{carnot}} \qquad [10]$$

Equation (1-10) are used to design a water chiller system that is more efficient during operation as given shown in Figure 4.

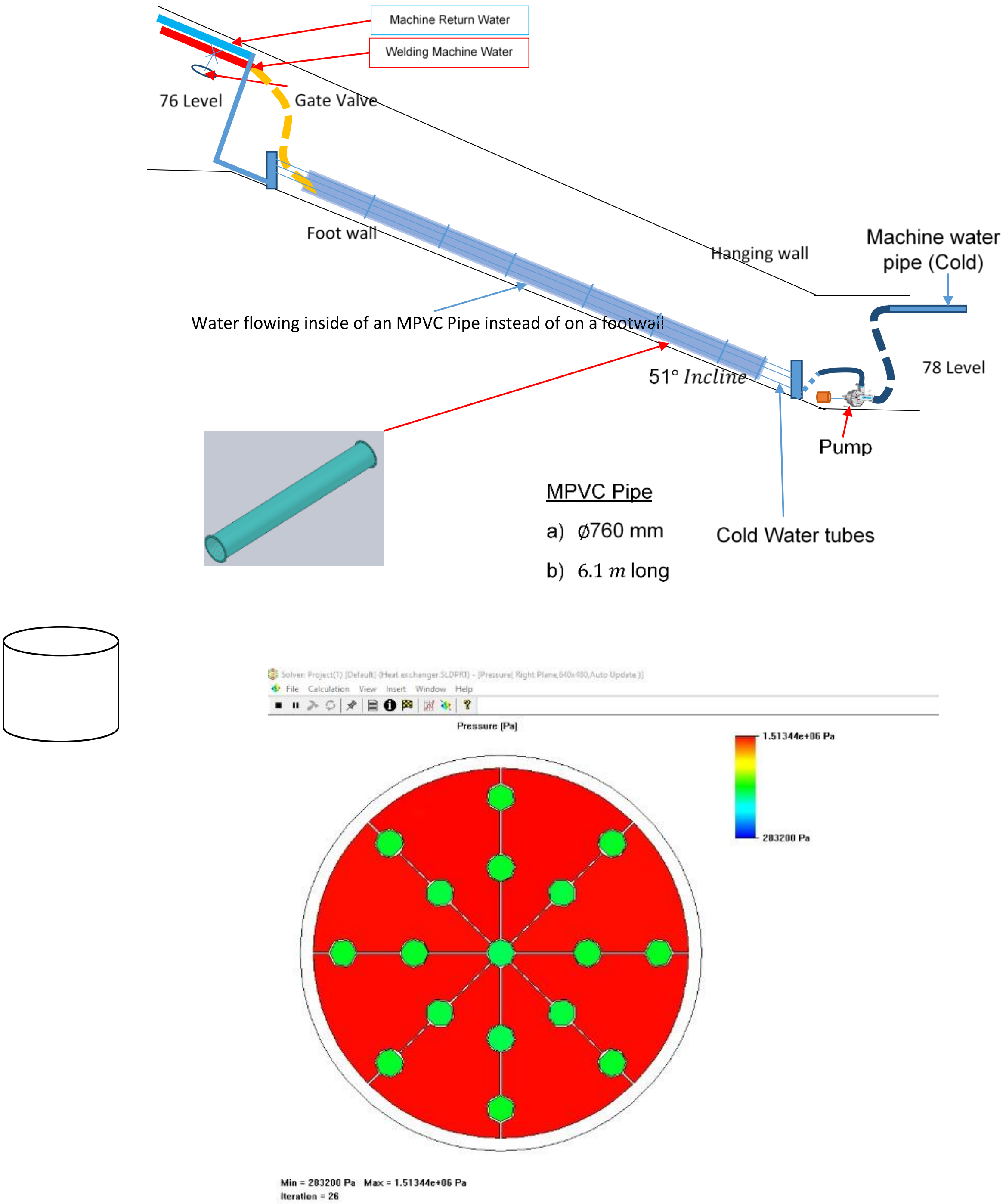

Figure 4: Heat Exchanger Design Cross Section

Experimentation considered the Kern and Bell-Delaware methods which were presented by performing Thermal Analysis and Hydraulic Analysis separately for the tube-side and for the shell-side. The rationale behind these choices was that the Kern method offered the simplest route, and the Bell-Delaware method offered the most widely accepted method, however, the method adapted in the research was the Kern Method. Kern method was developed to attempt and correlate data for standard exchangers by a simple equation analogous to equations for flow in tubes. This method was restricted to a fixed baffle cut (25%) and could not adequately account for baffle-to-shell and tube-to-baffle leakages. Kern equation was not particularly accurate, it did not allow a very simple and rapid calculation of shell-side coefficients and pressure drop to be carried out and has been successfully used since its inception. The flow of water in the system and the system performance was tested. A settler is a device used to adjust the quality of water by setting the heavy particles in the water that have been accumulated through scaling of the water tubes in the water chiller system. It is necessary to adjust the quality of water (solid particles formed because of scaling) in the chilling water process to ensure better mass flow rate which will improve the heat transfer as shown in Fig.5.

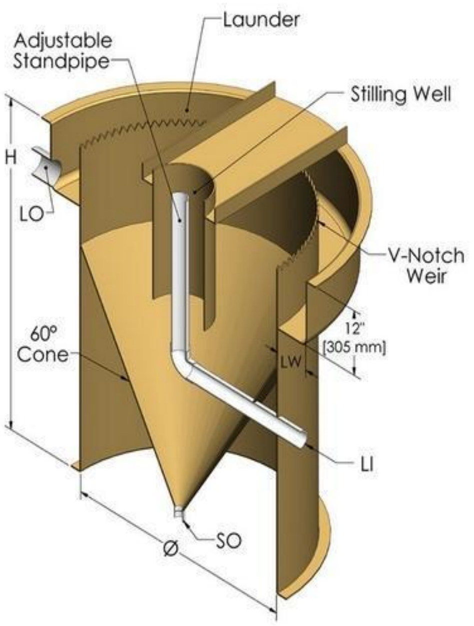

Figure 5: Solidworks Drawing: Cross section of a settler

The way in which a settler operates is that the muddy water will enter the settler at some point near the middle of the settler, gradually filling the settler with water causing the level to rise. The most important factor in the settling of the water is the rate at which the water rises in comparison to the rate at which the particles sink. If the rate of the water rise is too high, the particles in the water will not have time to settle out. The settler water entering through a launder into a down pipe into the center of the settler, where the water discharges roughly halfway down settler. The water then hits a diffuser so as not to disrupt the mud that has settled at the bottom of the settler. The water then rises in the settler at a speed that is dependent on the diameter of the settler. The water flow into the settler must be equal to that out of the settler as the volume is a constant, so at the top of the settler, the clear water is taken via a set of launders, while the heavy scaled particles that accumulates at the bottom is discharged into a filter. The layout and operation of a settler can be seen in the figure 6.

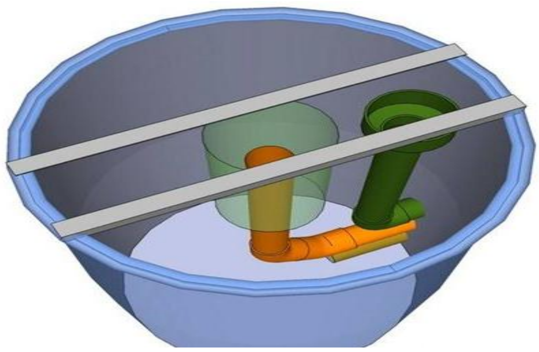

Figure 6: Solidworks Drawing: Simulation of a settler

Micro-Station software was used to simulate the performance of the settler. The parameters considered for simulating settler is the settling rate, (millimeters per second vs the settling speed in seconds) and the parts per minute. Water can be seen after having passed the flocculent but before entering the settler and after having left the settler. Looking closely at the water before it enters the settler, flocculent has started to work as the scaled particles have already begun to group together, giving a milky appearance. The water quality at the exit of the settler needs to be tested each shift to ensure that the water is within specification. The maximum tolerance for the particles in the water is 25ppm and the minimum pH level is 8.3. To maintain the correct pH levels, lime is added in the launders before the flocculent gel blocks. There are three different types of flocculent that are available depending on the conditions that are present: anionic, cationic and a combination of the two. The different flocculants are to accommodate for the differently charged particles which are present in the water, which will vary between locations.

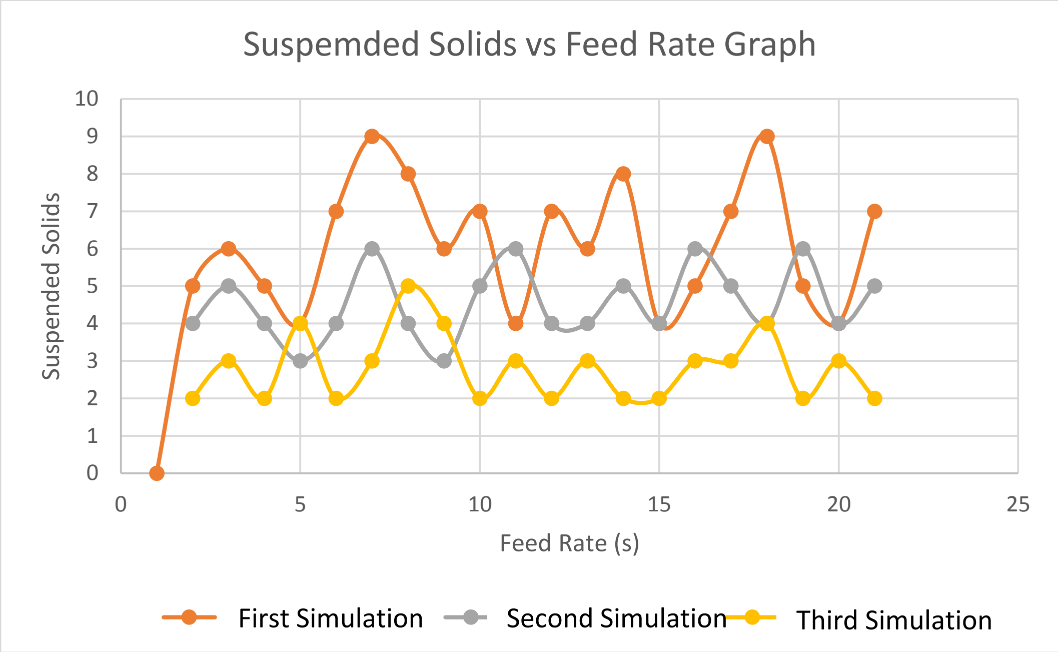

Figure 7: Results: Suspended solids vs feed rate

The suspended solids in the settlers ranges between 5 and 10 taken measured in different times of the day such as day, afternoon night shift. T this indicated the fast bonding of soil particles forming a solid mass particle, which in turn increased its mass over a period and settles on the bottom of the settler. It was observed that a rate in which suspended solids flow in, depends on the strength (adhesive) of the flocculent gel including the mass flow. During a mixing stage, micro particles collides and bonds to result into a larger particle called pinflocs. The water is ready for sedimentation state when the flow has now reached it maximum size particle. A contact time of flocculation normally ranges 10 to 15 minutes or more. A great attention must be focused on the mixing velocity and amount of energy.

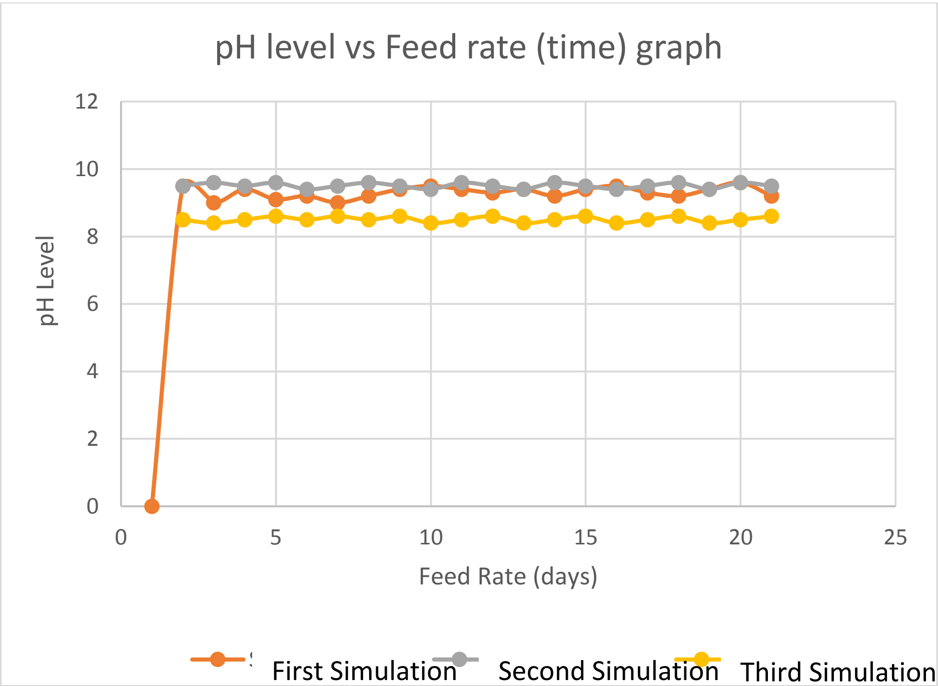

Figure 8: pH level vs feed rate (days)

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The pH level is also improved, and it ranged between the 9 & 9.5. That reduced the alkaline content of water, therefore scaling and slit built up will take place at a very low rate over the time. There are variations with regards to the Ph level and contributing factors were (a) Fluctuating mass flow rate and (b) Process temperature variance. The obtainment of reliable measurement results depends on the use of high-quality equipment, daily checks of electrodes, measuring instrument in good condition and strictly adhering to the operational and maintenance procedure

CONCLUSION

The aim of the current study was to improve the performance of the chiller system during operation. To achieve this objective, it was important to design a water chiller layout with improve mass flow of water in the system during operation. The varying parameters that improve the performance of the system was taken into consideration during operation. The result shows that the optimized system is more efficient during operation. The suspended solids in the settlers ranges between 5 and 10 taken measured in different times of the day such as day, afternoon night shift. It was observed that the rate in which suspended solids flow in the system depends on the strength (adhesive) of the flocculent gel including the mass flow. It was also shown that the pH level was also improved in the system, and it ranged between the 9 & 9.5. That reduced the alkaline content of water and therefore scaling and slit built up will take place at a very low rate over the time. The results also revealed that there are variations with regards to the pH level and contributing factors were fluctuating mass flow rate and (b) process temperature variance.

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