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NEW APPROACH FOR EARLIER HEAT DETECTION IN INDUSTRIAL FIELD

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ABSTRACT:

A Piston pump is a type of positive displacement pump in which the high-pressure seal alternates with the piston. Piston pumps are used to move liquids. The pumps can operate over a wide range of pressures and high-pressure operation can be achieved without a strong effect on the flow rate. This type of pump works through a piston and an oscillating mechanism that causes pressure differences. Each movement of the piston releases an equal volume of fluid, which is equivalent to the volume occupied by the piston during its stroke. Piston pumps are often used in scenarios that require high pressure, such as water injection systems in BMS wells. It is known that the amount of energy produced by friction within the PCU should be low and stable, therefore in case of failure, more friction appears and is converted into thermal energy.

The key point here is to detect this temperature change at the earliest moment (in the transition phase) typical of abnormal friction, rather than waiting for the temperature reach a high value. We are faced with two types of overheating dynamics. A very slow one that can last several days, and another fast dynamic that can occur in a few minutes. A new calculation algorithm has been designed and implemented in the DCS that can detect both overheating dynamics. The result has been an early anticipation of typical PCU failures due to overheating with a saving in repair costs of over 50%.

KEY WORDS: Piston Cylinder Unit (PCU), root mean square (RMS), Distributed Control System.

I. PCU FAILURES:

PCU is the acronym used for Piston Cylinder Unit and can be considered as the heart of the pump. Due to its importance, it is subject to strict preventive maintenance because of an analysis derived from the experience of use and the manufacturer's guidance. Despite such strict preventive maintenance, the BMS' WEPUKO injection pumps use to have an average failure time because of PCU every 2 months, which means an average cost of 170,000 euros per year for this problem.

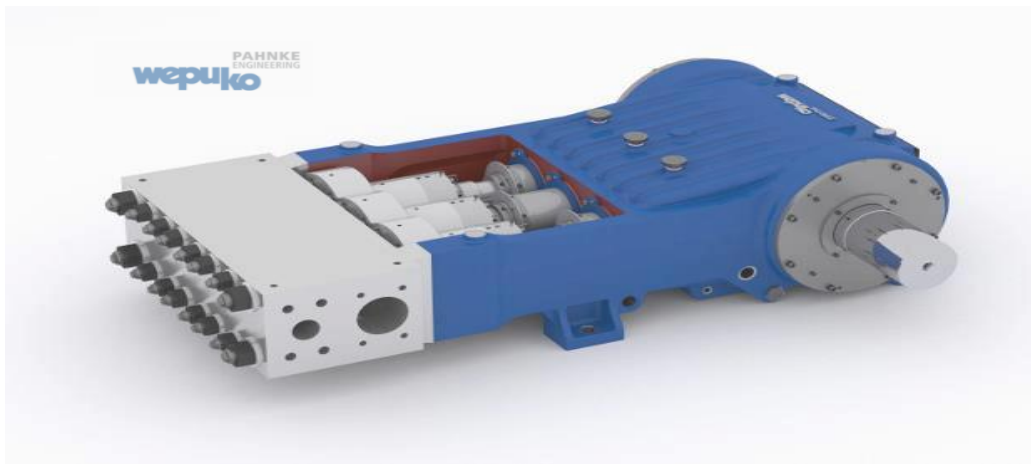
I.1 UNDERSTANDING THE ISSUE:

The water injection pumps in the BMS oil field are very critical in terms of production. Their purpose is to inject water at very high pressure into the reservoir to maintain its pressure and oil production at the desired level. The PCU can be considered as the main part of the horizontal piston water injection pumps. It is built in two parts, one static (Cylinder) and the other moving (Piston). While the pump is running, the plunger slides continuously inside the cylinder liner. Therefore, the PCU will be a place of high friction that can create scratches on the surface of the cylinder liner, due to heat accumulation and induced vibrations. To overcome this drawback, there is continuous lubrication of the contact surfaces along with freshwater cooling of the cylinder. Therefore, both the lubricating oil and the cooling water must be maintained when the pump is in operation to avoid damage. However, many undetected faults, such as clogging or leakage, can occur in both the lube oil and cooling water systems.

In addition, internal parts such as the packing or ring can be damaged, resulting in overheating of the PCUs. According to our estimates, this type of failure more than 70% of the time the pump is damaged. The solution to prevent these problems is to monitor the temperature of each cylinder and stop the pump when it reaches

a high value. This remote monitoring system was installed at BMS in August 2018. However, this solution is still unsatisfactory because the pump is triggered only after the PCUs have been running at high temperatures for a certain time, resulting in a pump shutdown with broken PCU internals and high spare parts consumption.

To improve the reliability of this monitoring system, a new approach based on online temperature data processing is applied. The principle is to continuously compare the sensors with each other and at the same time recognize a suspicious sudden change in temperature. This solution is intended to provide an early indication (alarm) of the suspected malfunction. Therefore, the pump can be stopped in advance before it operates in severe conditions, regardless of the fundamental causes of the malfunction. After the shutdown, a thorough mechanical overhaul of the PCU can be carried out, which will certainly result in lighter and more economical maintenance work. Before going further in explaining the proposed improvement and for a better understanding, we will explain the details of the current monitoring and control system.



II. THE EXISTING MONOTORING SYSTEM:

At BMS Each pump has got three PCU units Fig.1, on the top of each cylinder, a temperature sensor (PT100) is inserted and connected to local PLC through temperature transmitter (TT) with 4-20mA loop signal. The PLC perform the raw signal processing and communicate the temperature data to a remote supervision system (DCS) in the control room through Modbus Communication Protocol. The sampling frequency is 1 Hz, meaning that we have for each sensor a recorded value every one second.

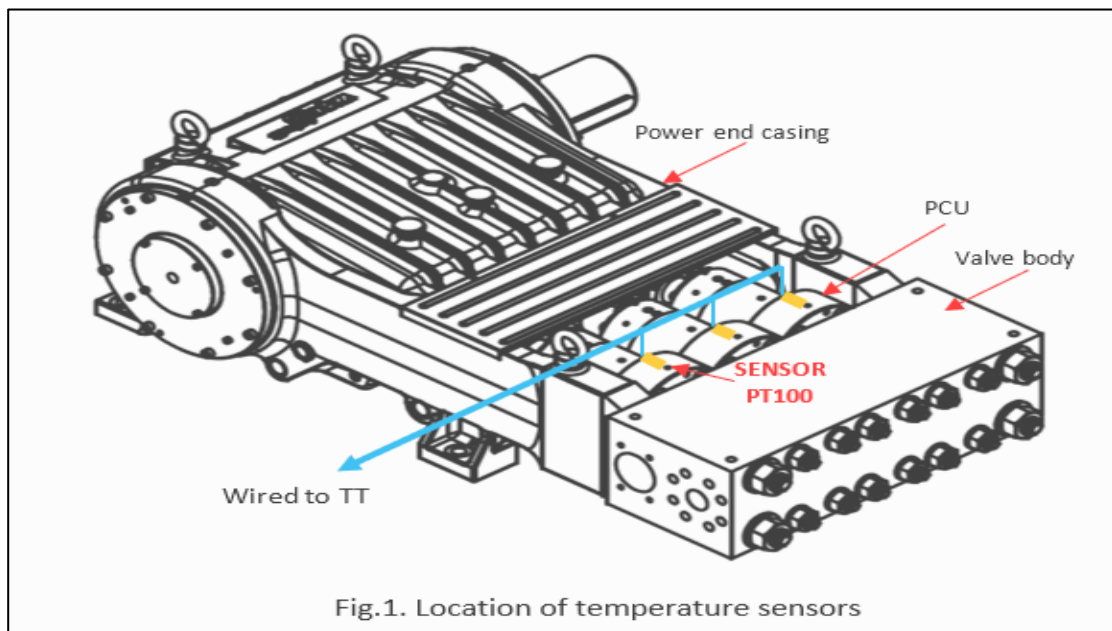
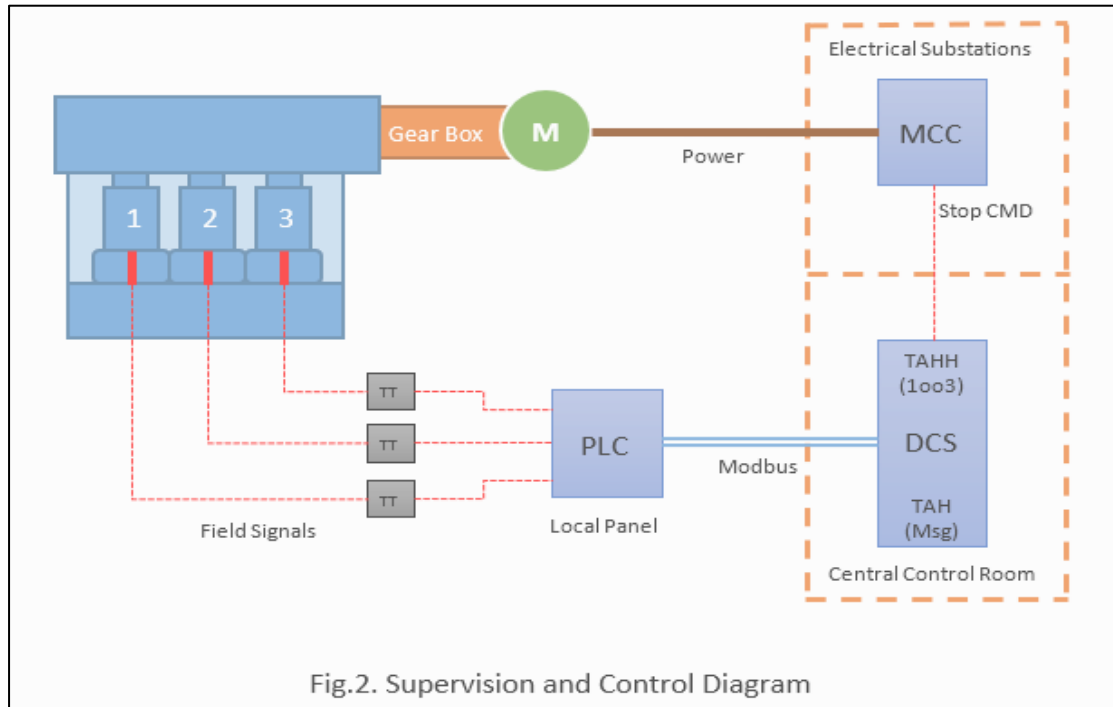


Fig.1. Location of temperature sensors

When the temperature reaches a value of TAH= 55 °C the DCS will set an alarm message of Temperature Alarm High to operators in the control room. Then, if the temperature continues to increase and hit the value of TAAH= 60 °C (Temperature Alarm High-High), stop command signal is sent automatically from DCS system to electrical substation to power-off both main motor and auxiliaries. This logic of control (interlock) is shown in the diagram of Fig.2.



Despite the above safeguard interlock, it seems that this solution is very limited for the following reasons. The first is that the set values for the alarm and trigger are too high, the damage is still very significant at the time of the trigger. However, instead of damaging the crankshaft, which can be disastrous, only the PCU is lost. The pump must be stopped much earlier. On the other hand, it is not possible to lower the alarm and trip values without having them overlapping with an ambient temperature that can easily reach 55°C during the summer. If we do so, it will lead to many spurious stops, therefore, if we want to stop the pump properly in advance, we must be able to detect any hidden information in the temperature trends of the cylinder. In doing so, we must consider the extent of the ambient temperature and the slow dynamics of the heating/cooling process.

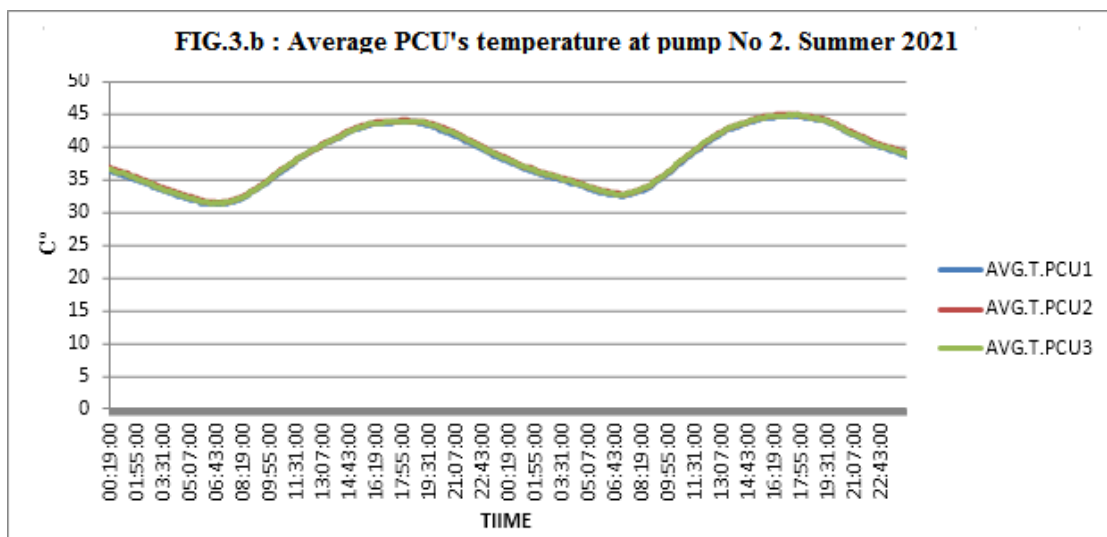
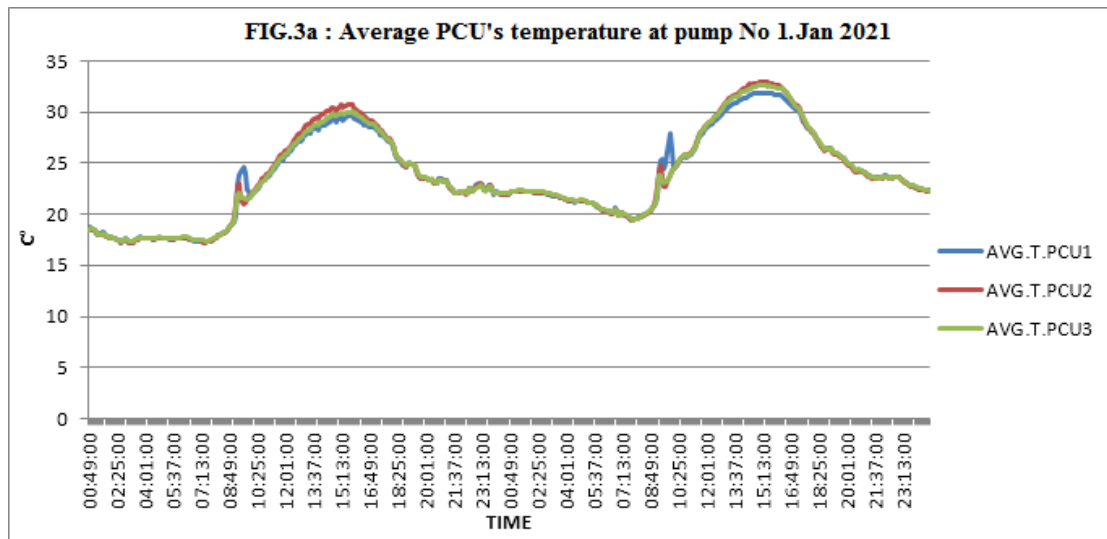
III. DATA ANALYSIS:

III.1 HEALTHY TRENDS ANALYSIS:

On the other hand, before the incident occurs, we can notice that there is abnormal trivial behavior when we compare the temperatures on the three cylinders. But it is not easy for the operator to keep his eyes on these values all the time trying to deduce any malfunctioning from small changes. The lack of quantitative indicators makes any attempt to recognize malfunction patterns very difficult and continuous monitoring by the system impossible as well.

On the typical trend of three temperature sensors for the healthy running pump. In FIG.3a & FIG.3.b the daily average values for each healthy PCU have been plotted with an average sampling rate of 6 minutes. The

data was collected during both winter and summer 2020 for water injection pumps 1 and 2, respectively. When the PCU is healthy all three sensors have a close value within a small-time span calculated by equation 1 where T1, T2 and T3 are respectively the temperature at the 1st, 2nd, and 3rd PCU.



III.2 THE DISPARITY:

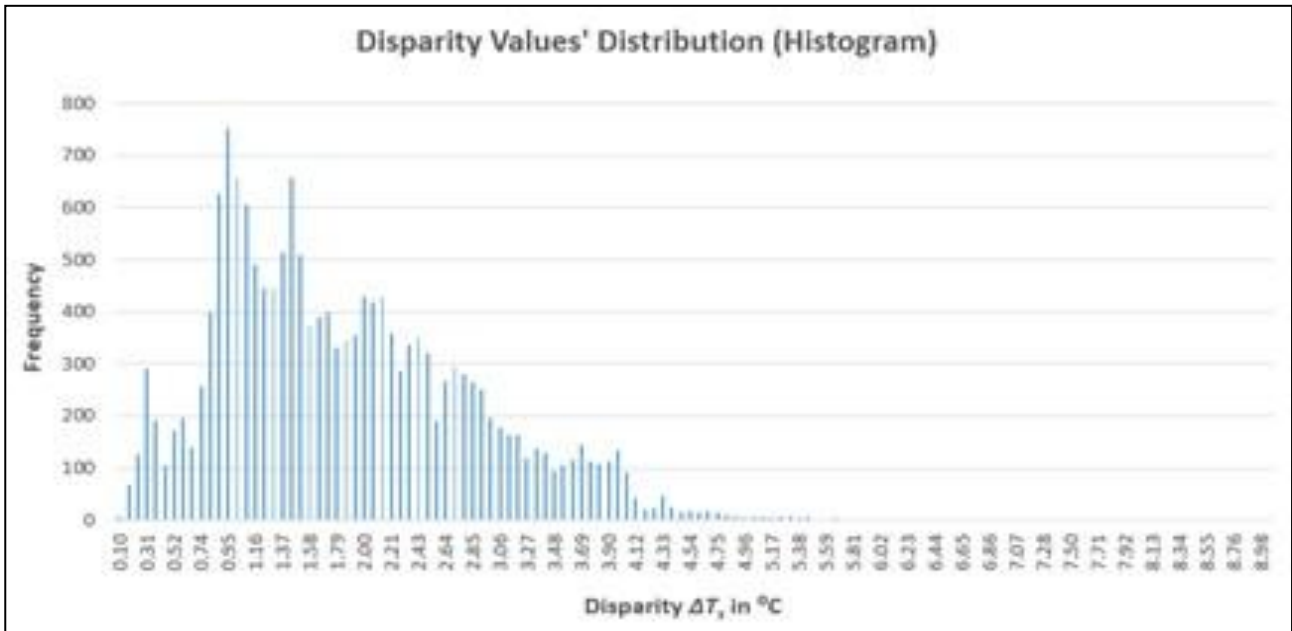
ΔT_S is the Disparity and can be caused by many factors, the main one being the transfer of heat from the cylinder to the probe, due to the position of the probe away from the cylinder. On the other hand, the integrity of the wiring can be altered even if the compensation cable is used, introducing a change in the probe resistance due to the high level of vibration. Other sources that may be at the origin of this difference are the quality of the cooling, the accuracy of the calibration and the environmental interferences. Together they make it impossible to obtain the same temperature in all three PCUs. Besides, this disparity can be significant during the start-up transient phase (heating) because when the pump reaches a permanent steady state all values are close together. The low friction at that time creates a very small heat transfer that is almost similar in all three PCUs. This heat transfer is not sufficient to make the measured temperature on the cylinder surface considerably different from the ambient temperature, particularly during summer, 16.800 measuring points were collected from the five pumps during an "assumed" good run-time equivalent to 14 days and used as

reference data for the healthy running condition. Statistical analysis of this population has given 1.91°C as the mean value of the disparity, with ± 1.02 °C standard deviation, minimum at 0.01 °C and maximum at 9.19 °C. It has been also observed that 99.4% of the disparity values are below 5 °C (16701 out of 16800 points). The disparity was calculated using the equation 1.

Eq.1

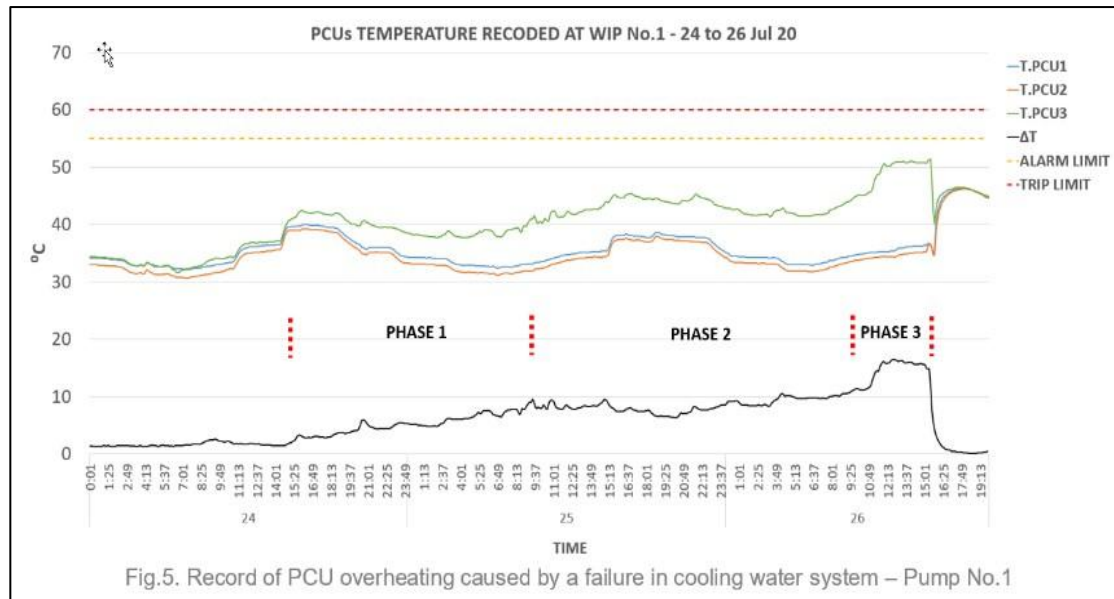
$$\Delta Ts = \max [|T1-T2|, |T1-T3|, |T2 - T3|]$$

The below histogram shows the distribution of the data collected:

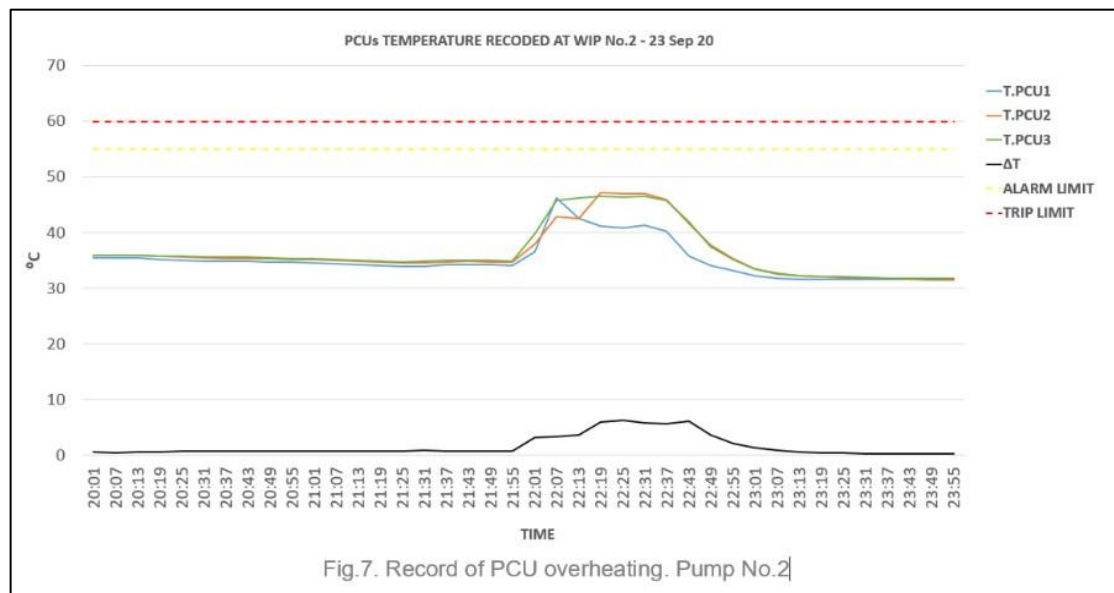


III.3 THE FAULT TRENDS ANALYSIS:

A typical PCU failure is shown in Fig.5 where the temperature was recorded at the PCU of pump 1 from 23 July at 10:00 to 26 July at 23:55. The pump was stopped on July 26th at 15:25 by the operator after it reached a high temperature at PCU No.3 with the disparity of $\Delta TS = 16^\circ\text{C}$. The trend of ΔTS can be broken down into three phases of overheating. The first phase begins at 46 hours before the pump stopped and the temperature at PCU No.3 is observed to slowly increase and continue to rise on a slight slope for 16 hours until it reaches $\Delta TS = 9^\circ\text{C}$. This is the transient phase in which, due to the failure, heat is transferred from the inner side of the PCU to the surface of the PCU by conduction. The second phase is constant and lasts 18 hours with a slight decrease in ΔTS due to the heating of the ambient temperature. The last phase is characterized by the rapid growth of $\Delta TS = 16^\circ\text{C}$ probably due to the high level of friction caused by the slow degradation of the internal parts of the PCU, the disparity has almost doubled in less than 9 hours. The pump operated under these conditions for 3 and a half hours until it stopped. We were informed that the lack of cooling water was the origin of this problem. The damaged parts were the stuffing box, the packaging, and the bottom ring. This type of failure represents most of the overheating phenomenon related to the gradual degradation of an internal component of the PCU.



The three PCUs may get overheated simultaneously without showing a significant difference between them preventing us to detect any important disparity (less than 6.5°C). However, the dynamic of such overheating is very fast regarding the previous slow drift case. Indeed, the temperature can rise by 10°C within few minutes as shown above in Fig.7



As a part of his duty, the operators are checking periodically the temperature values and their disparity to choose whether to stop or to keep running the pump. The operators used to wait until the PCU's temperature reaches high values or disparity between sensors begin to be signed before stopping the pump. This hesitancy can last for many hours and the operator may wait for the advice of process engineer or mechanical engineer to stop the pump. Also, it has been noticed that the disparity grows slowly at the beginning then it rises quickly without reaching alarm limit. If the operator is busy at that time with managing other parts of the process, he will not be able to notice the abrupt change since there is no alarm. Passing that moment, the action is taken to stop the pump comes too late and the casualties can be very high (ea. loss of crankshaft, bearing...). Hence,

the ideal situation is to stop the pump properly in advance just at the beginning of the trouble during early phase 1 as shown in Fig.5

IV. NEW APPROACH FOR EARLIER HEAT DETECTION:

It is clear after all that has been seen that we are facing two types of overheating dynamics. The first is very slow and can last several days. The other is a fast dynamic and can occur in a few minutes. Hence, we should be able to detect both of them. We can do it by two ways:

- 1- Enhanced spatial comparison between sensors to detect slow drift.
- 2- Time-based comparison for each sensor to detect sudden changes.

The new calculation algorithm implemented in the DCS was first tested with real data through simulation and detects both heat dynamics by first making an improved spatial comparison between the sensors to detect slow drift, and by applying a combined temporal drift of all the sensors to detect sudden changes. Both parameters are standardized at 5°C based on statistical analysis. All this means that below 100% we are within the normal situation and above 100% temperature growth is detected as abnormal. A pre-alarm was set at 90% to be more conservative, thus providing decision tools that help the operator to decide beyond the simple observation of the disparity between the values of the sensors' temperatures, it should be possible to obtain a more efficient indicator.

IV.1 ENHANCED SPATIAL COMPARAISON TO DETECT SLOW DRIFT:

We need to improve the simple method of observing the Sensor Disparity ΔTS to distinguish the fault independently of the effect of ambient temperature, measurement uncertainty and other disturbances that introduce a baseline deviation with a magnitude close to 15°C during the extreme situation, instead of immediately comparing the differences between the temperatures of the PCU and then selecting which is abnormal, we will use a simple and effective formula that gives a single parameter. Thus, the new parameter noted ΔAs will be calculated by the following equation (eq.2).

$$\Delta As = 100\% \frac{1}{5} \sqrt{\frac{1}{3} [(T1 - \min(T1, T2, T3))^2 + (T2 - \min(T1, T2, T3))^2 + (T3 - \min(T1, T2, T3))^2]} \quad \text{Eq. 2}$$

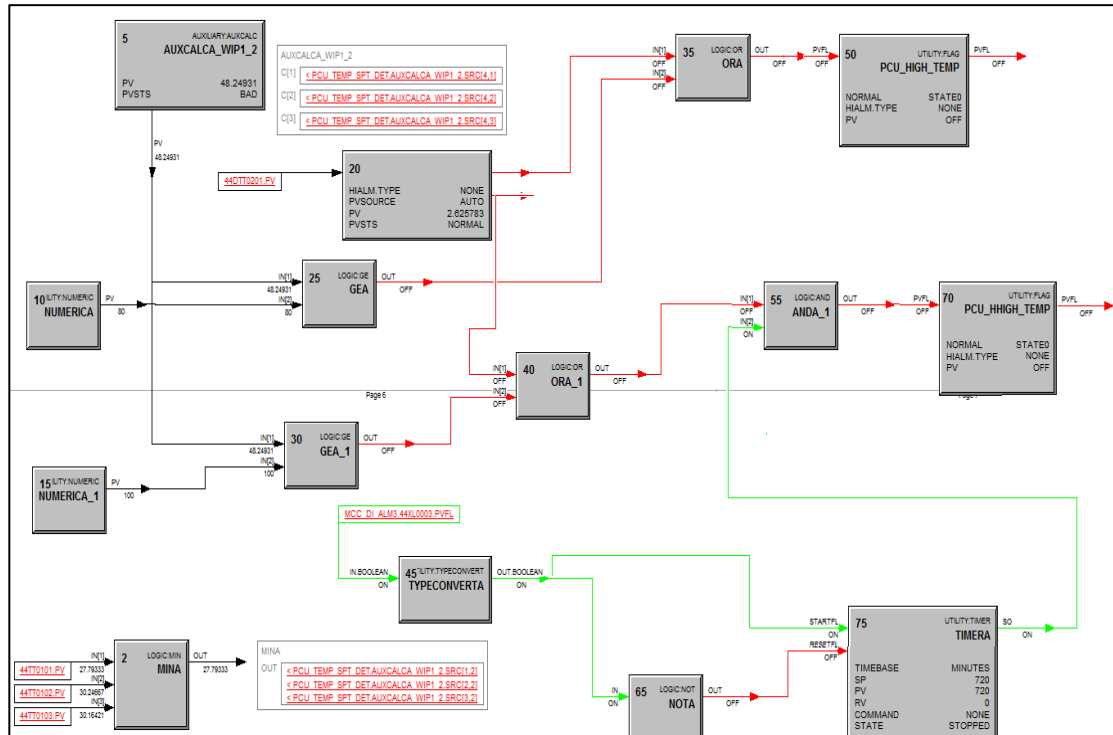
This formula will calculate the root mean square (RMS) of the differences between the minimum temperature value between all PCUs and the temperatures of the other PCUs. The lowest temperature is considered a reference and is assumed to be the most reliable, meaning that there is no abnormal friction in that PCU. The largest interval between the highest temperature PCUs is ΔAs . Simply the extra heat dissipation made by friction due to the failure is represented by the factor ΔAs . Also, to obtain immunity to measurement uncertainty we consider 5°C to be the minimum difference between the healthy and the bad PCU and normalize ΔAs to this value. The normalized square root filters out the lower disparity values, while the higher values are emphasized. Consequently, the trend of ΔAs is smoothed out and will only change if there is a significant disparity. In other words, we reduce both unwanted faults and spurious alarms. This method is suitable for tracking the slow dynamics by comparing the temperature of the PCUs that are supposed to be equal, rather than tracking the moving average by collecting a large amount of data over a long period. Furthermore, this method is independent of the fluctuating baseline made by the heating and cooling cycle of the ambient temperature (e.g. day and night, summer, and winter).

IV.2 TIME-BASED COMPARAISON FOR DETECTING SUDDEN CHANGES:

In addition to the above, another parameter that can be applied is the TEMPERATURE TIME DERIVATIVE ΔTt of each PCU considering that in case of failure in one PCU the others may be working well. Unlike ΔAS , which detects a slow fluctuation, ΔTt reflects the rapid change in trend that seems to have sharp edges. After studying the trends of several cases, we have noticed that the most serious damage will occur when there is a sudden change in 5°C within a 30-minute interval. Below 5°C it will be difficult to distinguish between measurement noise and actual deviation. This abrupt change of temperature in the unhealthy PCU should be normalized to 5°C. In the following equation (Eq.3), $dT1$, $dT2$ and $dT3$ are respectively the temperature at the 1st, 2nd, and 3rd PCU recorded in the previous 30 minutes.

$$\Delta Tt = 100\% \frac{1}{5} \sqrt{\frac{1}{3} [(T1-dT1)^2 + (T2-dT2)^2 + (T3-dT3)^2]} \quad \text{Eq. 3}$$

The below figure shows an example of the implemented algorithm in the DCS:



V. Conclusion:

A new calculation algorithm has been designed and implemented in DCS that can detect both overheating dynamics. The result has been an early anticipation of typical PCU failures due to overheating with a saving in repair costs of over 50%.

Through this Implementation we have got two new factors for every pump that were combined as following along with minimum difference value criteria to avoid spurious alarm during cold time:

- Threshold for high alarm for both DAs & DTt.
- Combine logic Alarm (DAs + DTt) = Trip.
- Reset manual.

- Bypass at start up until steady state is reached for 24 HRS to close a full day-cycle.

This algorithm will be further improved with new data from the pump sensors.