A low-cost automation system to minimise energy consumption of circulation pumps and to regulate the chemical composition of the water in swimming pools.

Design and cost analysis of an automation system for swimming pools

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There are many expensive swimming pool automation systems on the market at present. Designed to lower the energy consumption of the swimming pool pump, a standard swimming pool automation system can cost up to R 25 000. Most of these systems will only work on salt water (saline) swimming pools with installed chlorinators.

Swimming pool automation systems that automate acid and chlorine swimming pools are even more expensive. For this project, the focus was specifically on the automation of swimming pools using acid and chlorine. Of all the tests that must be performed on a swimming pool to keep it in a good condition, two stand out above the rest: chlorine level and pH level. The chlorine level is an indication of how much active sanitiser is in the water. The active sanitiser is the chemical responsible for killing unwanted bacteria. For this active sanitiser to function properly, the pH level must be kept between 7,2 and 7,4 [1], [2].

An oxidation reduction potential (ORP) probe was used to measure the active sanitiser level. This probe produces a voltage that is directly proportional to the active sanitiser. A pH probe was used to measure the pH level. This also produces a voltage that is proportional to the pH level. When these two tests are combined with a controller, the chemical composition of the water in the swimming pool can be controlled successfully.

For this project, the ORP and pH probes were used together with a Siemens S7-200 programmable logic controller (PLC). The two sensors were connected to the input of the PLC and two chemical feeders (chlorine and acid) were connected to the unit's output.

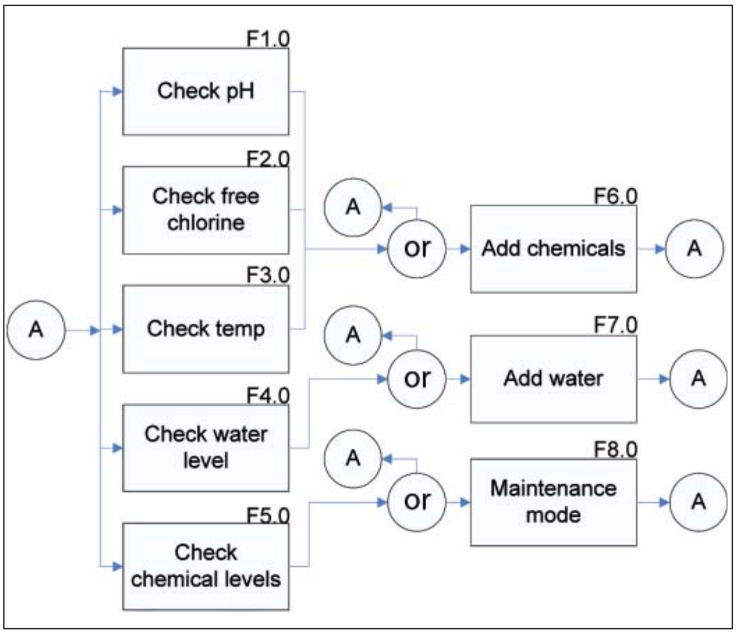

Fig. 1: System breakdown structure.

When the active sanitiser level is too low, the system calculates the amount of chlorine required and activates the chlorine feeder. The system then checks to see if the pH level is correct and calculates the shortfall. The system was implemented in such a way that the sensors were connected to the swimming pool's water.

Automation systems: an overview

A swimming pool can be described as a small-scale water treatment plant [4]. The condition of a swimming pool depends greatly on how well the chemical properties are monitored and corrected. Swimming pool automation systems have been developed to take care of day-to-day maintenance. They

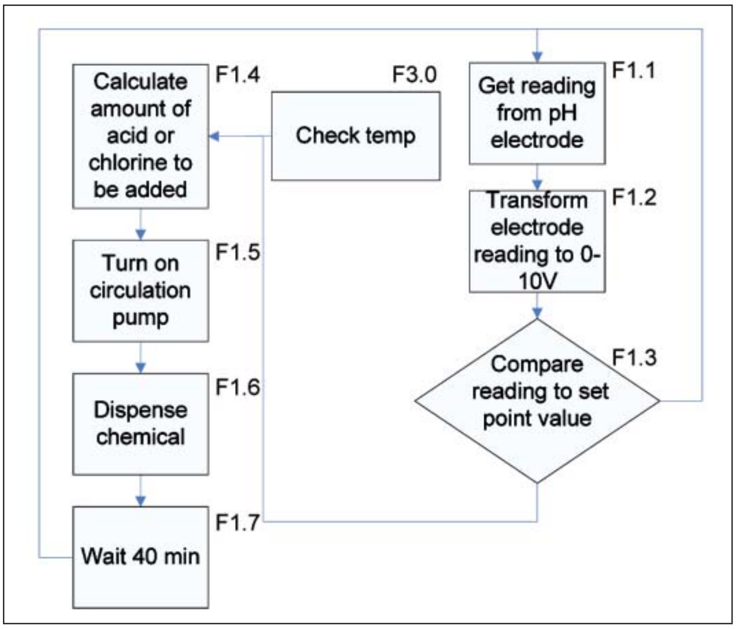

Fig. 2: Function block F1.0.

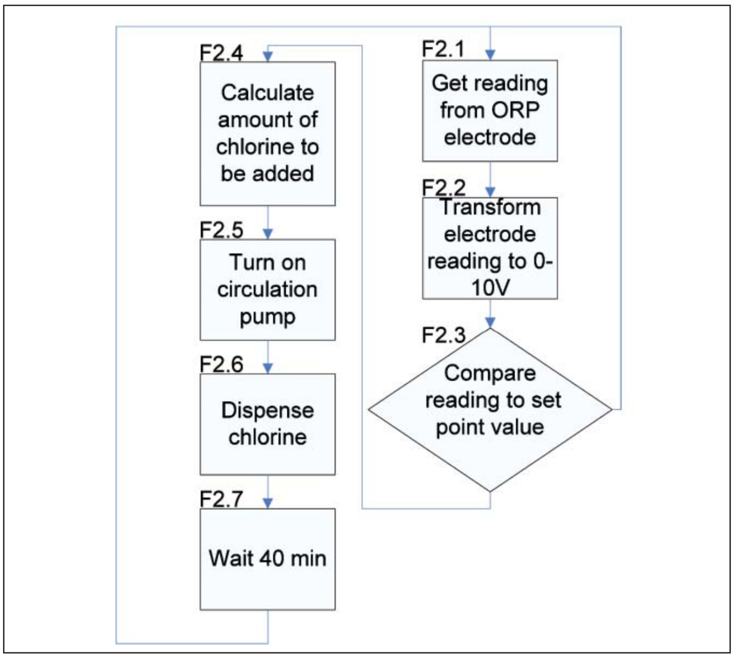

Fig. 3: Function block F2.0.

can control the lights, temperature, filtration system and water level [6].

Swimming pool chemistry

When chlorine is added to water, it forms HOCl (hypochlorous acid) and HCl (hydrochloric acid) as shown here [9]:

$$Cl_2+H_20 \rightarrow HOCl+HCl \quad (1)$$

The HOCl partially dissociates into:

$$HOCl \rightarrow H^+ + ClO^- \quad (2)$$

The formed HOCl and ClO (hypochlorite ion) are known as the free available chlorine. The free available chlorine is the collective name for the chemicals needed for disinfecting [8]. A high level of free available chlorine is needed to keep the swimming pool sanitised. Hypochlorous acid is a better disinfectant than the hypochlorite ion. These two chemicals' formation is determined by the pH of the water [10].

If the pH is kept at 7,5 the maximum amount of hypochlorous acid will be 50%. Hypochlorous acid and the hypochlorite ion are the active ingredients in the solution. Hypochlorous acid can combine with other chemicals such as ammonia and form new compounds that are not good sanitisers, typically referred to as "chloramines". When these chloramines are formed, they are called combined available chlorine [5].

If the combined available chlorine level becomes too high, the water must be shock-treated, the process of adding a high amount of chlorine to produce new HOCl and ClO^-. In some cases the water must be replaced because the total dissolved solids (TDS) is too high.

Oxidation reduction potential

Oxidation reduction potential is the only effective method to measure free chlorine levels electronically. Oxidation is the exchange process of electrons between two atoms of different substances. One atom will receive an electron and the other will lose one. There is a constant balance between oxidation and reduction. The atom that receives an electron is reduced, and the atom that loses an atom is oxidised [11].

All swimming pool sanitisers like chlorine and bromine are oxidisers. These sanitisers have the ability to oxidise (take an electron from) other compounds. This process destroys organic matter and bacteria, keeping the water free from any unwanted substances [8].

The ORP meter measures the potential of the sanitiser to oxidise. If new oxidiser is added to the water the ORP meter will give a high reading as electrons are exchanged and all unwanted substances are destroyed. As the sanitiser gets reduced, its ability to oxidise decreases and so does the ORP reading [10].

The ORP can therefore be seen as a direct indication of the activity of the sanitiser. It is a measure of the free chlorine in the water [5].

The ORP probe consists of two electrodes: a reference electrode and a measuring electrode. The reference electrode is made of silver and is surrounded by a salt electrolyte. The measuring electrode is made of a platinum band. The reference electrode produces a constant reference voltage and is used to measure the potential difference between the two electrodes. The electrodes are submerged in the water to be measured, the water connects the two electrodes and a potential difference is generated between them. [12, 13].

PH sensor

The pH sensor consists of two electrodes: a reference electrode and a measuring electrode. The voltage generated between the two electrodes is directly proportional to the pH of the solution [7].

At a pH of 7 the generated voltage will be 0. At a high pH, the sensor will generate a voltage of one polarity and at a low

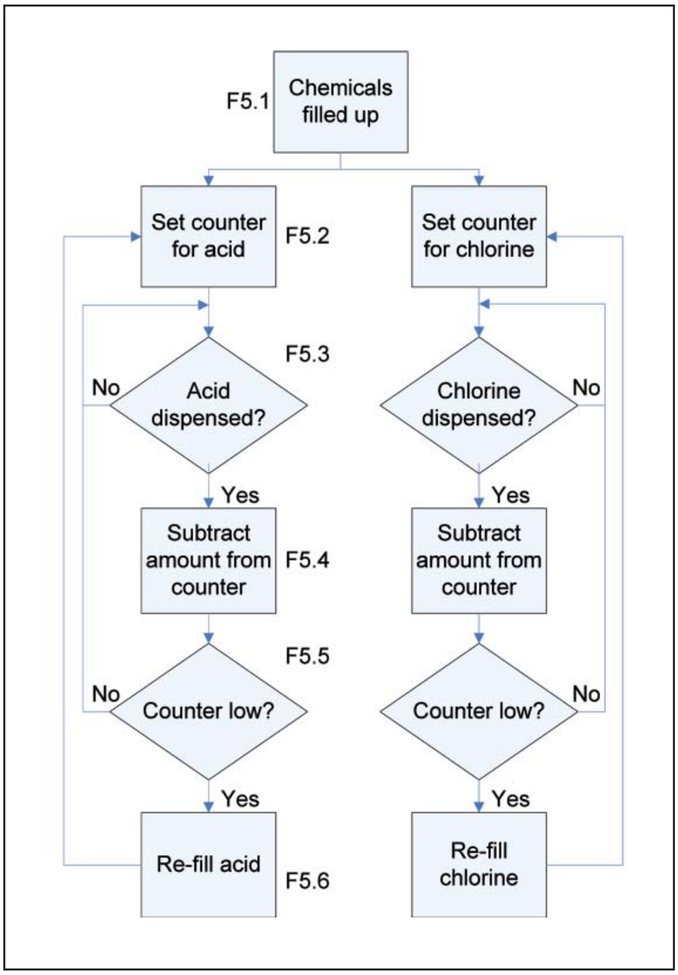

Fig. 4: Function block F5.0.

pH, the sensor will generate a voltage of opposite polarity. The generated voltage of a pH sensor is affected by the temperature of the solution. If the temperature of the measured solution stays relatively constant, there is no need to compensate for temperature. If the temperature of the measured solution fluctuates, temperature must to be taken into account.

The reference electrode is made from a solution with a pH of 7. This solution is separated from the water by a porous separator. This allows for ions to be exchanged from the solution inside the electrode with ions in the water, and gives a low resistance from the electrode to the water. The other (measuring) is from a glass membrane that only allows H+ ions to pass through [14].

If the measuring electrode is placed in a base, there will be more H+ ions in the solution of the measuring electrode. These H+ ions will pass through the membrane into the base, leaving an excess of OH- ions in the solution of the measuring electrode and generating a negative voltage [3].

Behaviour analysis

The swimming pool automation system is divided into function blocks F1.0 to F8.0, as shown in Fig. 1. Each of these function blocks is divided into smaller function blocks to explain the system's logical breakdown structure.

Block F1.0 (Check PH)

This function block is responsible for checking and correcting the swimming pool's pH level, which must be kept between 7,2 and 7,8. This function block is divided into seven smaller function blocks as shown in Fig. 2. The pH electrode will be submerged in the swimming pool water. The electrode will generate a small voltage that is proportional to the pH of the swimming pool's water. This voltage must be scaled to a maximum voltage of 10 V, as the PLC's analogue input voltage is between 0 V and 10 V. F1.2 therefore represents a high impedance voltage amplifier circuit.

In function block F1.4, it will be decided which chemical, and how much of it, to dispense. If the pH is too low, chlorine needs to be added. If the pH is too high, acid needs to be added. It is noted that the pH probe is sensitive to temperature (F3.0), and needs to be taken into account. The system will calculate how much of each chemical to dispense depending on the size of the swimming pool and how far the pH is off. The algorithm for this calculation and the change due to temperature can only be done through experimental tests.

Fig. 5: Experimental test setup system.

Before the chemicals can be dispensed, there must be a flow of water to distribute the chemicals evenly though the swimming pool. The main circulation pump will be turned on to establish this flow of water. The chemicals will then be dispensed into the pipeline.

Block F2.0 (Check free chlorine)

This function block will constantly monitor the free chlorine level as shown in Fig. 3. South African law states that all public swimming pools and spas must have a minimum ORP voltage of 600 mV. The ORP electrode will measure the available free chlorine in the swimming pool's water. As with the pH sensor, the reading from the ORP sensor will be stored in the PLC. If the ORP reading is less than 600 mV the system will advance to the next stage, because this means that the active sanitiser level is too low and may pose a danger to the user. If the level is above 600 mV the system will return and constantly check the free chlorine level.

The amount of chlorine to be added will depend on the ORP sensor reading. The exact amount will depend on how far off the reading is from the pre-set value. As in the case with the pH sensor, the circulation pump must be turned on to distribute the chlorine evenly. The chemical feeder will receive a signal produced by F2.4.

This signal will be time-dependent and will also depend on the amount of chlorine to be added. The more chlorine to be added, the longer the signal will stay active. There will be a waiting

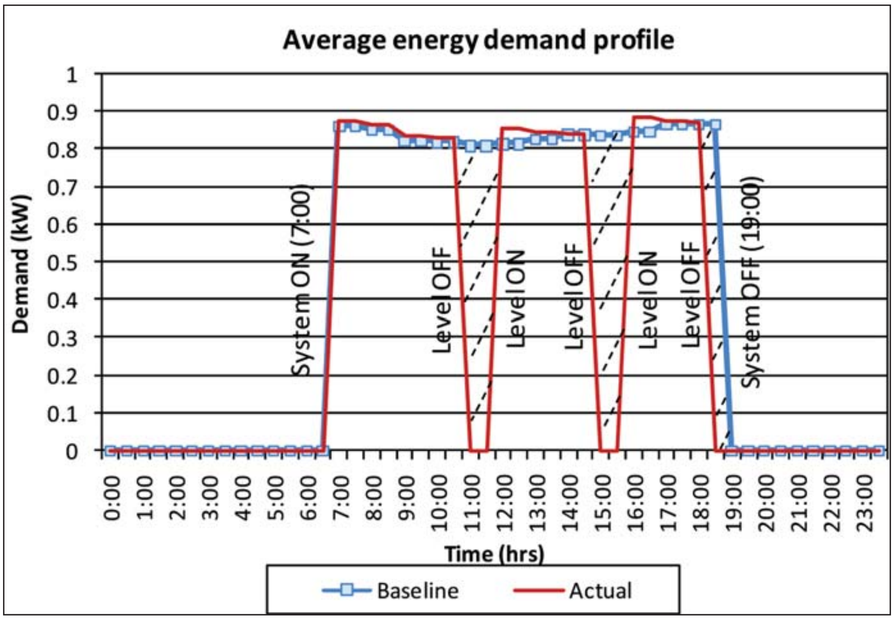

Fig. 6: Average energy demand profile for the automation system.

period before the sensor will check the free chlorine level of the swimming pool's water. This will give sufficient time for the dispensed chlorine to dissolve and get disturbed evenly.

Block F3.0 (Check temperature)

Some swimming pools have heaters installed to warm the water. The pH sensor's reading is sensitive to change in temperature and must be adjusted depending on the water temperature. The exact deviation in pH due to the change in temperature must be calculated through experimental tests. A thermocouple was used to check the temperature. The thermocouple produces a varying resistance that is directly proportional to the temperature of the swimming pool's water.

Block F4.0 (Check water level)

The swimming pool's water level will be monitored constantly by means of a float sensor. It is important to monitor the water level because the pH and ORP sensors can be damaged if not submerged. The signal received from the sensor is a contact that is open when the water level is correct, and closes when the level is too low. This is why there will only be two preset values for the water level, "high" and "low".

Block F5.0 (Check chemical levels)

The chemical level will be monitored by a program in the PLC. The program will calculate the theoretical amount left in the container. Each time the chemicals are dispensed, a counter will be updated with the amount of chemicals left (see Fig. 4). The procedure for acid and chlorine is exactly the same.

The chemicals must be filled up for the first time. This will set the counter that represents the level of the chemicals. A counter is used to determine how much of the chemical is still left in the container. An internal variable word will be used in combination with a down counter. This value will be displayed on the HMI.

The system will constantly monitor when a chemical is dispensed and will stay in a loop until a chemical is dispensed. The system will go out of the loop if a chemical is dispensed, triggered by function block F1.4 or F2.4. The amount that will be subtracted will be determined and an algorithm will be programmed that calculates the amount to be subtracted from the counter, depending on how much of the chemical is dispensed. The counter in F5.2 will be updated with the new value after the chemical has been dispensed.

The system will check the amount of chemical left after each dispense. If there are enough chemicals in the containers, the system will go back and wait for an input. If the chemical level is low, the system will go into "refill" mode, F5.6, and the containers must be refilled. On the containers are marks displaying percentage values. These values will be captured on the HMI when the containers are refilled. This will reset the counter with the new value.

Blocks F6.0 and F7.0

Function blocks F6.0 and F7.0 are the physical output blocks. Function block F6.0 is the chemical feeder that will be triggered to dispense either acid or chlorine. Function block F7.0 will be triggered when the water level is too low.

Experimental results, cost analysis

For the experimental test setup of this project, a 210 l drum was used. The ORP and pH sensors were mounted inside the drum to make contact with the water (see Fig. 5). Almost the same results are expected when installing the automation system at a swimming pool.

The chemical feeder is mounted on the wall of the drum so that it dispenses the chemicals directly into the water. A small pump was used to circulate the water and chemicals into the water.

Interface circuit for PH sensor

When designing an interface circuit for the pH sensor, it must be born in mind that the input impedance of a pH sensor is in the order of 1 GΩ. An op-amp is therefore required to match the input impedance of the pH sensor. The interface circuit for the pH sensor is divided into three different stages; buffer, offset and scaling. The pH sensor must be connected to a high impedance input op-amp. The next stage is to give the signal from the pH sensor a positive voltage for when the signal from the pH sensor is negative. The pH sensor produces a negative voltage above a pH of 7 and a positive voltage for a pH below 7.

The pH sensor produces 50 mV per pH. The minimum voltage produced by the pH sensor is therefore 7 x 50 mV, which yields 350 mV and will be the positive voltage of set. This further means that that the new range of the pH sensor is from 0 V to 700 mV. The last stage is to amplify this voltage to a voltage that is accepted by the analogue module from the PLC, which is a voltage from 0 V to 10 V.

The signal is represented by an integer value between 0 and 32 000 when the pH sensor is connected to the PLC via the interface circuit. One needs buffer solutions with exact pH values for this value to be useful. The pH sensor's output voltage is directly proportional to the pH value and vice versa.

ORP sensor

The ORP sensor produces a voltage between 0 V and 1000 mV. This voltage is a direct indication of the chemical

Item	Cost
Siemens PLC	R3500
ORP probe	R3200
Siemens HMI	R2500
pH sensor	R450
Total	**R9650**

Table 1: Actual system cost including PLC and HMI.

Item	Cost
Microchip PIC	R50
ORP probe	R3200
pH sensor	R450
Total	**R3700**

Table 2: Estimated system cost.

Item	Cost
Zodiac pH perfect	R12 000
Clearwater chlorinator	R18 000
Poolwarden	R9500
Pentair 52054	**R20400**

Table 3: Similar pool automation systems.

activity and shouldn't be manipulated as we are looking for this exact value. This value is too small for the analogue input module of the PLC and must be scaled. The easiest way is to multiply it by a factor of 10. Thus, the new output is 0 V to 10 V. When the ORP sensor was placed in tap water, it produced a voltage of 4 V, which was actually 400 mV before it was amplified. This is an acceptable ORP reading for tap water.

Automation system

The automation system consists of the two sensors that measure the chemical properties of the water and, accordingly, adjust the values to a predefined set value. When the ORP reading falls below 300 mV the chlorine feeder turns on. The amount of chlorine dispensed is directly proportional to the time the feeder is on, approximately 5 mg per second.

When the chlorine is dispensed, the circulation pump turns on to distribute the chlorine evenly through the whole tank. The pump is on a predefined timer which switches on at 07h00 and off at 19h00. The normal, 12 hour running time is taken as the baseline condition (see Fig. 6). When the pH level is too high, above 7,6, the automation system dispenses acid into the water and when the pH is too low, it activates the chlorine feeder. If the correct level is reached, the automation system switches the pump off. After an hour, the pump is switched on again and the water quality is verified. The system continues this process until 19h00, after which the pump is switched off. The data provided in Fig. 6 is for a 48 000 l swimming pool operated for 12 hours under normal operating conditions. Operating time is reduced to 9,5 hours with the inclusion of the automation system.

Cost analysis

The system was designed to function under laboratory conditions. The total cost to build the system was R9650 (see Table 1).

The PLC and HMI were only used for demonstration purposes and can be excluded to reduce the overall cost. The system can be build for around R3700 including VAT at 14% (see Table 2).

Table 3 provides estimated costs on different automation systems. The Pentair 52054, Poolwarden and Zodiac pH Perfect are swimming pool automation systems that use the ORP and pH sensors as inputs from the swimming pool. The Clearwater chlorinator system works only on salt water systems.

Conclusion

The swimming pool automation system has the ability to lower the energy consumption of the swimming pool pump.

The system was simulated using a 210 l drum filled with water and tested on a 48 000 l swimming pool. The two sensors were placed inside the drum. Connected to the drum were also two chemical feeders, one with chlorine and one with acid. The results of the chlorine test and pH test were displayed on a HMI connected to a PLC.

A reduction in the average energy consumption can be seen from the experimental test setup system. For a swimming pool to be healthy, there must to be enough active sanitiser to kill the bacteria in the water.

The easiest method to test for the active sanitiser is to make use of an ORP sensor. These can cost between R3500 to R20 000. When using a pH sensor in conjunction with an ORP sensor, one can manage a swimming pool to a great extend. For this project, a Siemens PLC and Siemens HMI were used to control and monitor the system. The HMI for this project was used purely for demonstration purposes.

The most economical pool automation system available in South Africa was found to be the Pool Warden system at R9500. The total cost to build the automation system was R9650 (R3700 excluding the display). The automation system regulates the chemical composition of the water in the swimming pool and lowers the energy consumption of the circulation pump by switching it off when the correct chemical composition is achieved.

Acknowledgement

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