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DEVELOPMENT OF A VOLUMETRIC FLOW RATE SET-UP USED FOR THE EVALUATION OF A PERMANENT MAGNET AND THE EFFECT IT HAS ON SCALE FORMATION IN A TUBE

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ABSTRACT

An experimental investigation is described in which an experimental set-up and measuring technique is developed. It is used to evaluate a permanent magnet for the decrease of scale formation in tubes. The volumetric flow rate is used as the indicator of scale formation, which relies on the basic principle that the friction pressure drop increases if scaling takes place. The test section consists of three soft drawn copper tubes in which water with a velocity of ± 2 m/s flows. One of the tubes is used to evaluate the Physical Water Treatment (PWT) device and the other two tubes are used as a control. With the experimental set-up described it is possible to detect a change in the friction factor of 1% which represents a flow rate change of 22 mℓ/min. Experiments are conducted in different phases in which the PWT device is attached onto one of the tubes and then removed to determine if any change in the scale formation rate takes place. It follows from the results obtained that a very sensitive experimental set-up was designed and built with which very small amounts of scale can be detected. However, contradictions in the experimental results makes the set-up unusable for the evaluation of the efficiency of PWT devices.

INTRODUCTION

Since the first physical water treatment (PWT) patent was registered in 1945 by Vermeiren [1], hundreds of these PWT devices have appeared on the market that are reported to reduce scale formation and blow-down requirements without chemical treatment. The efficiency of PWT devices for the prevention of scale is a controversial subject. Parker *et al.* [2] for example, surveyed approximately 60 papers on this subject. They have found that many contradictions exist in the claimed effects, and that even when performance is reported to be effective, the results are typically characterised by low reproducibility. Busch *et al.* [3] state that "No agreement exists on optimum operating parameters that should be used". From this discussion it can be concluded that thorough research is necessary in which an experimental set-up is built with which it is possible to determine the effect PWT devices have. It is also necessary to describe the experimental procedure and experiments done in detail so as to produce reproducible results which will clarify the questions surrounding PWT devices. The aim of the work done is therefore to describe the procedure followed in developing a measuring technique which is used in an experimental set-up.

NOMENCLATURE

D = diameter of tube [m]
f = friction factor for primary losses
g = gravitational acceleration [m/s^2]
h_{lT} = head loss [m^2/s^2]
k = coefficient for secondary losses
L = length of tube [m]
m = mass [kg]
p = pressure [Pa]
Q = heat transfer [J]
t = time [s]
u = internal energy [J/kg]
V = velocity [m/s]
y = height [m]
e = average roughness of pipe [m]
μ = viscosity [Ns/m^2]
ρ = density [kg/m^3]
$\dot{V}$ = flow rate [m^3/s]

EXPERIMENTAL SET-UP

The experimental set-up is designed to measure changes in flow rate through tubes when scale formation occurs. The experimental set-up is shown in Fig. 1 and the top view of the part just before the fouling tubes is shown in Fig. 2.

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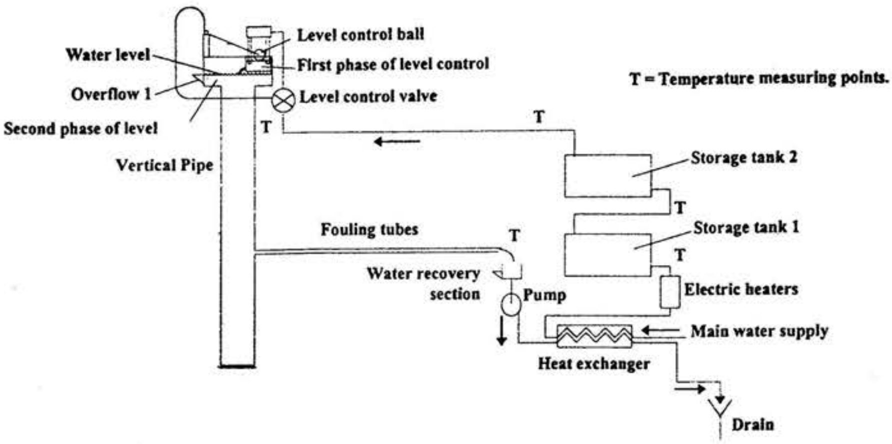

Figure. 1: Schematic representation of experimental set-up.

The once through experimental set-up receives water from the main water supply with temperatures of 18°C. It is first heated to approximately 38°C with a counter flow tube-in-tube heat exchanger. The water used for the heating is hot water which has passed through the system. After the heat exchanger the water is further heated with five, 4 kW electric heaters. The water is then finally heated to 53.5°C in two, 200 ℓ storage tanks (geysers) connected in series. This temperature is chosen as scale formation is better at higher temperatures. With this set-up it is possible to control the water temperature variation in the tubes to within ± 0.5°C.

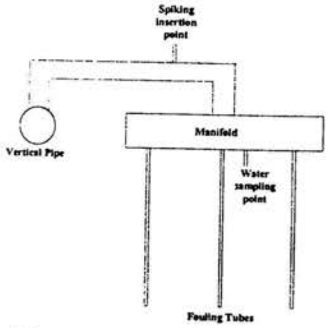

Figure. 2: Top view of test section

All the heating of the water is done before the fouling tubes so that the temperature of the water in the tubes is exactly the same.

After the storage tanks the water passes through a level control section which consists of a level control valve, level control indicator and level control ball. The ball is situated in the first phase level control container. The first and second phase level control is used to control the height of the water to a constant value (within ± 1mm).

The second phase container has an overflow through which the excess water flows. A sampling point is inserted at the overflow.

The height of the water in the vertical column to the centre line of the fouling tubes is 4.16 m. This height ensures a velocity of approximately 2 m/s in the tubes of the test section.

The manifold which is connected to the vertical water column is used to divide the flow into the three tubes (test section). A spiking insertion point is added to the set-up. This is done so that chemicals can be added to the water. The second sampling point is inserted just before the fouling tubes. The fouling tubes used in the set-up are soft drawn copper tubes with an inside diameter of 6.52 mm and a length of 4 m. The flow rate of the water in each of the fouling tubes is measured after the test section. The flow rate through the test section or fouling tubes are determined by measuring the time it takes to fill a known fixed volume. The container used is made from PVC, has a volume of ± 215 ℓ, and is 1.82 m high.

A parameter which is very important and must be controlled is the temperature of the water in the fouling tubes (within ± 0.5°C) and for this reason the whole set-up is covered with insulation. To be able to monitor the temperature variation, temperature measuring points were made (Fig. 1).

DESIGN OF THE EXPERIMENTAL SET-UP

Determining the pressure head

The primary aim with the experimental set-up is to detect any volumetric flow variations. A decrease in the volumetric flow indicates that scale is forming. The diameter of the tube in

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which fouling occurs will decrease and this change will increase the flow resistance and thus decrease the flow rate through the tube, which can be measured accurately. This change in velocity will then in turn influence the Reynolds number.

It is also possible that the surface roughness of the tube will change. A factor which will take all these changes into account is the friction factor. The diameter of the tube can be used as an indication of the scale formation but it is difficult to detect very small changes in small diameter tubes. For this reason the analysis for the experimental set-up is done so that a very small change (1%) in the friction factor will be detectable and this change will then also be detectable with the experimental set-up. It will be indicated later in this section that a change of 1% in the friction factor represents a measurable change in the volumetric flow rate.

To do the analysis it is assumed that the initial volumetric flow rate is produced with a velocity of 2 m/s in the test tubes. This velocity is chosen because it is the velocity which is most commonly used in industry. The analysis is done as follow: One dimensional, steady state, incompressible fluid flow with no work being done by the set-up is assumed for the analyses. For these conditions, Eq. (1) can be written as follows if it is noted that point 1 is at the entrance to the fouling tubes and point 2 is at the exit of the fouling tubes.

$$\frac{p_1 - p_2}{\rho} = \left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right) + g(y_2 - y_1) + \left[-\frac{dQ}{dt}\frac{dt}{dm} + (u_2 - u_1)\right] \tag{1}$$

The term $\left[-\frac{dQ}{dt}\frac{dt}{dm} + (u_2 - u_1)\right]$ represents the loss of "mechanical energy" per unit mass of fluid flowing. These terms can be grouped together and are called the head loss (h_{l_T}). With dimensional analysis, it is possible to determine an equation (Shames [4]) for the pressure loss due to flow in a tube with a certain diameter, length, velocity, density, viscosity and tube surface roughness. From this analysis it follows that:

$$h_{l_1} = \frac{V^2}{2}\frac{L}{D}\left[K\left(\frac{\rho VD}{\mu}, \frac{e}{D}\right)\right] \tag{2}$$

where K is a function. The head loss can therefore be written as:

$$h_{l_1} = f\frac{LV^2}{2D} \tag{3}$$

where *f* is the friction factor. When tube bends, valves, sudden enlargements and constrictions are used then another head loss term has to be added and it can be written as in Eq. (4). The value for *k* is approximately 0.78 according to Shames [4] at the entrance to the fouling tubes which is the value for a tube which joins another tube with an inward projection. The total head loss is then given by Eq. 5

$$h_{l_2} = k\frac{V^2}{2} \tag{4}$$

$$h_{l_T} = f\frac{LV^2}{2D} + 0.78\frac{V^2}{2} \tag{5}$$

At the entrance to the fouling tubes the conditions are not known and therefore Bernoulli's equation is used between the surface of the water in the second phase level control container and the entrance to the fouling tubes. The water velocity on the surface is zero and the pressure is atmospheric. Bernoulli's equation can be written as follow:

$$\frac{p_1}{\rho} = gy - \frac{V_1^2}{2} + \frac{p_A}{\rho} \tag{6}$$

If Eq. (5) and (6) are substituted into Eq. (1) and the following are assumed: p_2 is equal to p_A, because both are at atmospheric pressure, y_1=y_2=0 (the tube is horizontal) and $V_1=V_2=V$ (the diameter of the tube stays the same) then Eq. (7) is obtained for the height of the water in the vertical column.

$$y = \frac{\dfrac{f}{\dfrac{2\sqrt{\dfrac{\dot{V}4}{V\pi}}}{L}} + 0.89}{\dfrac{g}{V^2}} \tag{7}$$

Soft drawn copper tubes were used in the test section and for these smooth tubes the friction factor [5] is given by

$$f = \frac{0.3164}{R_{eD}^{\frac{1}{4}}} \tag{8}$$

where R_{eD} is the Reynolds number based on the diameter of the fouling tubes.

Determining the flow rate variations

With the height of the water column known for the specific set-up obtained from Eq. (7), it is now possible to: change the friction factor (simulating fouling taking place), keep the height term constant and calculate the new velocity (Eq. (7)) which will in turn give a new volumetric flow rate. This volumetric flow rate can then be compared with the volumetric flow rate worked out when no fouling has occurred to determine if the change will be detectable or not.

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Parametric study

With the equations derived a parametric study is done in which the diameter and length of the fouling tube as well as the height of the water column are varied. This is done to determine the dimensions of the experimental set-up which will give the largest flow rate variation for a fixed change in the friction factor. These dimensions are also influenced by the space available to construct the set-up and commercially available products. From this parametric study the following dimensions are obtained which produces the most sensitive set-up. Height of the water column = 4.16 m, length of copper tube = 4 m, inside diameter of copper tube 6.52 mm, volume of container used to measure the flow rate in the fouling tubes = 215 ℓ. With these dimensions the difference in time necessary to fill the container is between 14 to 15 s if the friction factor changes with 1%. It is only necessary to compare the time necessary to fill the container to be able to determine if the flow rate is changing as the volume of the container stays constant. The time necessary to fill the container can be measured within 0.2 s and a change in the friction factor of 1% will thus easily be noted. An 1% change in the friction factor represents 22m ℓ/min change in flow rate which is very small and shows how sensitive the set-up is. The set-up is very sensitive to temperature variations which is reflected in a change of 0.6 s in time necessary to fill the container for every 0.1°C change in temperature. It is also possible to detect very small changes in the diameter of the fouling tubes which is reflected by a 2.4 s increase in time necessary to fill the container for every 1 μm thick scale.

If it is assumed that the dynamic head and the loss at entrance to the fouling tubes can be ignored (the dynamic head is 20 times smaller than the static head and the entry losses is at least 23 times smaller than the frictional losses) Eq. (9) can be obtained. It gives the scale thickness as a function of the time necessary to fill the container. The values for density and viscosity are those found in Shames [4] at a temperature of 50°C. According to this equation the time difference for a 1 μm scale is 2.3s which corresponds very well to the value obtained with the parametric study.

$$s = 0.00326 - 0.06015 / t^{7/9} \tag{9}$$

EXPERIMENTAL WORK

The experiments were done over a period of 721 days. The experimental results were divided into sixteen phases and are summarised in Table 1. The variation in time necessary to fill the container over the whole period is indicated in Fig. 3. The time necessary to fill the container is indicated on the y-axis and is shown as the minutes above 47 minutes (47:38.4 is indicated as 38.4 s) and the day number on the x-axis.

In each of the phases the experiments were done according to the following procedure: The container is placed under the copper tube in which the flow rate needs to be measured. The container is then filled with water from one of the copper tubes but the time necessary to fill the container is not measured. This is done so that the amount of water on the inside of the container is the same for the first experiment as for the second and third experiment. When the container is full, the water flow at the top is redirected and the plug at the bottom of the container is opened so that the water can drain from the container. After 30 minutes the plug is replaced. It takes about ± 25 minutes for the water to drain from the container. The first test is then started and the time necessary to fill the container is measured. While the container is filling the temperature of the water entering the container is noted at 5 minute intervals. As soon as the container is full the plug at the bottom of the container is removed so that the water can drain and after 30 min the plug is replaced. The flow rate in the second copper tube is then measured and after that the third one.

During the experimental period water samples are taken weekly and analysed. This is done to determine whether the results obtained could not be influenced by the chemical composition of the water.

DISCUSSION OF RESULTS

Phase 1

For the first 21 days of experiments the difference between the maximum and minimum time necessary to fill the container are 2.2, 3.1 and 2.9 s. An increase of 14 s gives a decrease in volumetric flow rate of 22 mℓ/min. From these results it follows that no scale has formed. This phase could therefore be described as a cleaning phase in which all impurities such as oil are removed. The time difference of 10 s (0.4% on 47 minutes) to fill the container between the three tubes can be contributed to the manufacturing of the fouling tubes.

Phase 2

From the results of phase one it follows that no measurable scale has formed for at least 72 days of running the experiment. It was therefore decided to increase the rate at which the scale formed by increasing the calcium concentration in the water to 100 ppm (mg/ℓ). This is called spiking. By comparing an average line and a regression line for the different tubes it can be concluded that there was no overall change in the time necessary to fill the container. There is however a deviation from the mean and the standard deviation is larger than the standard deviation for phase 1.

Phase 3

According to the results obtained there is a definite increase in time necessary to fill the container for all three tubes in this phase. For tube 1 and tube 2 this increase is very similar but the increase for tube 3 is higher. For tube 1 and 2 there is a 59 s in-

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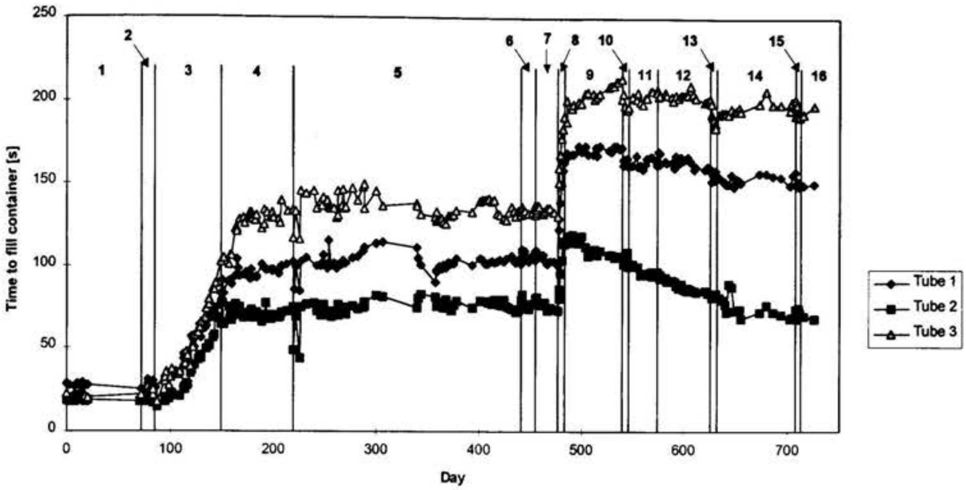

Fig. 3: Variation in time necessary to fill container.

Table 1. Description of different phases of experimental period

Phase	Period [days]	Description
1	72	Calibration and cleaning
2	6	Spiking with calcium solution
3	65	No PWT device
4	70	PWT device attached onto tube 3
5	222	No PWT device
6	14	PWT device attached onto tube 3
7	22	No PWT device
8	6	Spiking with calcium solution
9	58	No PWT device
10	6	Spiking with calcium solution and magnet attached
11	29	PWT device attached onto tube 3
12	51	No PWT device
13	6	Spiking with calcium solution
14	76	No PWT device
15	6	Spiking with calcium solution
16	12	No PWT device

crease in 65 days and for tube 3, 80.4 s. This difference represents a 0.7 % change in 48 minutes. According to the analytical investigation this increase is 62.4 mg or 0.27 μm thick scale per day over the length of tube 2, 0.266 μm in tube 1 and 0.38 μm in tube 3. The increase is thus very similar.

Phase 4

The permanent magnets (PWT device) were placed onto tube 3 (day 149) to determine the effect. The other two tubes would act as a control. From the results shown and calculations made it can be deduced that there is a 83%, 102% and 70% decrease in gradients for tube 1, 2 and 3 compared to the previous period of experiments. This definite decrease is visible in all three tubes and not just in tube 3.

Phase 5

The PWT device was removed to determine if the scale formation rate would be the same as in phase 3. From calculations done it is deduced that there is a small increase in scale formation for tube 1 and 2 and a decrease for tube 3. The difference is however very small (unlike the difference from phase two to phase three). A decrease in time necessary to fill the container for day 219 and 225 can be observed in Fig. 3. This decrease is visible for all three tubes.

Phase 6

The magnets were placed onto tube 3 for two weeks and then removed . This was done to verify the results obtained on day 219 and 225. There was however no reduction in time when the magnets were removed nor was there any scale removal observed in any one of the three tubes.

Phase 7

The set-up had to be left for a few days to determine whether it had stabilised. In the phase there was no significant variations in the flow rate.

Phase 8 and 9

During phase 8 the water was spiked and this time the scale formation increased as soon as the spiking started. This differed from the previous time when the scale formation

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started after the spiking had been stopped. The scale formation stopped as soon as the spiking was stopped.

Phase 10

In phase 10 the magnets were placed onto tube 3 at the same time as the spiking was started. In this phase there was not an increase in scale formation as in phase 8. This could indicate that the magnets had the effect of decreasing the scaling. The effect was however not only on the tube with the magnets attached but on all the tubes.

Phase 11

The magnets were left attached onto tube 3 to determine if the effect observed in phase 10 would continue. From the results it follows that the change from phase 10 to 11 is much smaller than the change from phase 8 to 10.

Phase 12

The set-up was left to stabilise with no magnets attached, before the results of phase 8 and 10 could be verified.

Phase 13

In phase 13 the water was spiked. This was done to verify the results obtained in phase 8. From the results obtained it follows that scale formed in tube 2 but was removed in tube 1 and 3. The increase in tube 2 was much smaller than in phase 8. These results contradicted the results in phase 8 completely. This indicates that the results in phase 10 were not due to the magnets.

Phase 14

The phase was used to stabilise the set-up, with no magnets attached, before the results of phase 13 could be verified.

Phase 15

The water was spiked in this phase with no magnets attached. Similar results were obtained than those in phase 13. It can thus be concluded that the results in phase 13 are correct. The conclusion in phase 10 that the magnets caused the reduction is thus not right.

Phase 16

Phase 16 was used to determine if the scale would not form as in phase 3. In this phase no spiking was done and no magnets attached. From the graph it follows that the results are not similar to those in phase 3.

From the short discussion for each stage it follows that many contradictions exist. In certain phases the magnets seem to have an effect *, in other phases it seem that the magnets had no effect ** and there were phases which contradicted one another ***. These different phases can be grouped as follow:

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a. As soon as the magnets were attached onto tube 3 in phase 4, the scale formation decreased in all three tubes.
b. As soon as the magnets were removed from tube 3 in phase 5 there was a sudden decrease in scale formation in all three tubes.
c. When the solution was spiked and the magnets were attached onto tube 3 in phase 10, there was a decrease in scale formation compared to phase 8.

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a. The sudden decrease in scale formation in phase 5 could not be reproduced in phase 7.
b. The scale formation rate did not return to the formation rate as in phase 3 after the magnets were removed in phase 5.
c. The results obtained in phase 10 with the magnets were similar to the results in phase 13 and 15 with no magnets which indicated that the magnets had no effect.

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a. Spiking in phase 2, 10, 13 and 15 did not cause the scale formation rate to increase, while the spiking in phase 8 caused an increase in scale formation rate.
b. After the spiking in phase 2 the scale formation rate increased in phase 3. This increase was not present in phase 9, 11, 14 and 16.

CONCLUSION

An experimental setup was designed and built with which very small amounts of scale formation can be detected by monitoring the volumetric flow rate. The volumetric flow rate monitoring tool is therefore a very good scale forming detector. Due to the fact that many contradictions exist in the results the experimental set-up can however not be used to evaluate the effectiveness of PWT devices.

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