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Redesign improvement of a hydrocarbon sampling tool using robust design

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The paper describes the redesign of a hydrocarbon sampler tool, which is an important tool used to obtain petroleum samples from the bottom of the reservoir, conserving its physical characteristics and carrying it to the surface, in order to characterize the problematic of wax and asphaltene precipitation over the production pipelines. The aforementioned phenomena is highly non-linear, so slight variations in temperature and pressure can spark irreversible changes of the fluid properties and produce diminished performance in the exploitation of the reservoir. The storage container that is a part of design is outlined. The container is used to obtain and keep a volume of hydrocarbon in a single phase and is a part of the hydrocarbon sampler tool, so laboratory studies can be conducted to assess correctly the reservoir condition. The new design must be capable of maintaining the pressure and temperature conditions of the sample through the sampling and analysis process. The storage container includes an automatic electric heater and temperature sensors installed on the container to restrain pressure variations through the control of the temperature. A reduction of the energy consume was achieved, improving up to 13% of the heat loss. For this stage of the project robust design was used, because it is an efficient and systematic methodology that applies static and dynamic experimental design to improve products and manufacture processes, and its focus is to make an output response insensitive to or robust to difficult to control variation (noise).

Keywords: Robust design; Hydrocarbon sampler tool; Petroleum flocculation; Petroleum reservoir tampering

1. Introduction

The problematic related to asphaltene precipitation and wax deposition has increased in the oil field; its importance cannot be ignore due to the economic damage occasioned in the hydrocarbon production. Researchers have discovered that this phenomenon may occur inside the pore space in the reservoir, down-hole well production pipelines, well heads, flow lines, separators and gas treatment plants.

In the case of pipelines, the cleaning of pipes and production strings is performed through chemical methods, thus increasing production costs (Leontaritis 1988). Many papers and much research about the problem have proposed mathematical methods to estimate the probability of precipitation occurrence (Victorov and Firozabadi 1996, Solaimany Nazar and Dabir 2001).

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However, this theoretical research cannot be fully proven until an original sample from the reservoir can be taken and kept in its original condition. This is the reason why it is necessary to design sampler tools, which can get samples from the bottom of the well, and control pressure and temperature variations.

Some authors suggest that asphaltene precipitation can be caused by electro-kinetics; however, the flocculation onset presence indicates mainly a thermodynamic nature. The asphaltene flocculation is therefore originated by changes in pressure, temperature and composition so that they can be extremely difficult to dissolve; indeed, in some systems, reversibility cannot be achieved at all.

The study of the phenomenon requires principally the knowledge of the crude oil composition and bubble point pressure. This can be obtained from experimental PVT analysis, which requires a previous extraction of a sample from the bottom hole. Nowadays there are many techniques to obtain real samples of fluids (American Petroleum Institute 1966, Jaramillo 2001). Companies and designers have built complex systems and tools to obtain samples since 1950s. Properly designed sampling tools are capable of collecting valid fluid samples from reservoir. However, as the tool returns to the surface, it is cooled by the environmental conditions, allowing the sample to shrink. These tools generally have a fixed internal volume, and consequently a phase separation can occur.

There have been three main trends for designing sampling tool up to now:

- The first uses basically open tubes with valves disposed at each end, operated by a mechanical clock. The pressure was controlled once the sampler reached the surface after taking the sample, injecting mercury into the tool to re-pressurize the sample to a point above the saturation pressure that controlled the pressure at the surface.
- In the second trend (generation), samplers used a piston, thus increasing the complexity. The volume of the sample chamber was still fixed, allowing the sample to be a two-phase state during the sampling process.
- In the final trend, single-phase bottom-hole samplers were designed. These used an over-pressurized nitrogen buffer to vary the sample shrinkage as the temperature was reduced during retrieval, allowing the sample to be kept at the same sampling pressure or above. However, the nature of the asphaltene flocculation phenomenon requires one to control the thermodynamic changes, and this type of tool is unable to control these characteristics.

Our proposal is towards a new trend. Using robust design we intend to improve the hydrocarbon sampler tool (HST), preserving pressure and temperature from the reservoir, keeping the physical parameters automatically in order to allow a better characterization of wax and asphaltenes.

The paper unfolds as follows. Section 2 explains the objective to create a new design of the HST. Section 3 defines some concepts of the robust design methodology. Section 4 gives a detailed description of the HST and the storage container. Section 5 explains the application of robust design to improve the storage container design. The following section analyses the experimental results to finally present the conclusion to built an optimized prototype.

2. The problem and objectives

Resuming, wax deposition in oil production and transportation has always been a serious problem, for which many operational costs are incurred. In spite of many studies being performed to characterize the phenomenon, they were made using oil samples with current sampling and analysis techniques, but irreversible changes to the fluid properties could have been introduced due to changes in temperature and pressure during the sampling and retrieval process. Until now, few sampling tools had been considered to control samples thermodynamically. The first version of the HST is one of them, which was built to allow retrieval of the sample to the surface, maintaining it at the flowing bottom-hole temperature – which means that the sample is subject to no thermodynamic changes whatsoever, as maintaining the sample temperature makes it possible to prevent the sample from shrinking, maintaining the pressure inside at flowing bottom-hole conditions. General characteristics of the HST are to be mentioned in section 3. In addition to the temperature maintenance facility, the sampler was designed to be capable of operating at 1 055 kg cm^{-2} (15 000 psi) of pressure and 175°C. Later in the paper, figure 2 shows a general scheme of the tool. Part number 3 is the storage container. It has the principal elements to measure and control the physical parameters of the fluid sample. In the first test in the laboratory, an uncontrollable heat loss was found. The consumed energy due to heat loss meant that the electric heater demanded more than 800 V and 0.980 A. Such conditions were over the limit of the specifications of the electro-mechanical cable, which is commonly used. This problem originated a new approach: to redesign the HST optimizing the latest design. To demonstrate the improvement of the tool, the case of the storage container is presented here, in which robust design was used.

3. The robust design method

An important aspect of the activity of the designers is to select a suitable method to design. In many cases it depends on the target of the problem. In the design of some parts of the sampler tool, like the storage container, robust design offers the possibility to obtain a good compromise among design variables and functionality, making the product 'robust' or insensitive to variations of environment. Some basic concepts about the methodology will be mentioned briefly.

Taguchi's philosophy on quality improvement emphasizes reducing variations in products and processes. Parameter design is intended as a cost-effective approach for achieving such reductions. It can be used either to build qualitative new products or to improve the quality of existing ones. Consider the product or process under study to be referred to as a system. Taguchi classifies the inputs to the system as follows:

(a) 'control parameters' or 'control factors', denoted by x; there are parameters/factors that can be easily controlled and manipulated,
(b) 'noise variables' or 'noise factors', denoted by z; there are variables/factors that are difficult or expensive to control.

Variation in z during the manufacture or operation causes variation in the system performance measurement by any quality characteristic y. Figure 1 is the P diagram used to explain this concept.

There could be many settings of x in which the system can perform, on the average at desired (target) levels. Among these, there will be some settings in which the system is insensitive to variation in the noise variables z. The basic idea in parameter design is to identify, through exploiting interactions between control parameters and noise variables, appropriate settings of control parameters in which the system performance is robust to uncontrolled variation in z. Because of this, the approach is called parameter design. The term 'design' here refers to the design of a system rather than the statistical experimental design. Since the goal is to set the robust system to be modified in noise variables, the approach has also been called robust design.

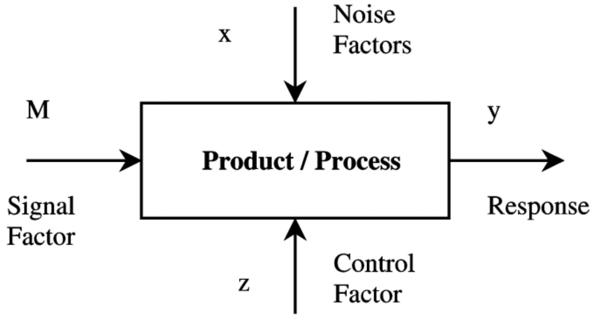

Figure 1. Block diagram of a product/process.

Taguchi has also proposed a collection of techniques to identify the settings of x that would achieve robust performance. These include statistical experimental design and analysis techniques. The control parameters x are varied according to an orthogonal array in each setting of the control parameters, and the effects of the noise variables are evaluated by varying them systematically using a 'noise' or 'outer' array. Taguchi also classifies parameter-design problems into different categories and defines a measure performance, which Taguchi calls the 'signal-to noise' (S/N) ratio, for each category. The estimated S/N ratio is analysed using standard analysis of variance (ANOVA) techniques to identify the settings of the control parameters that will yield robust performance.

Control parameters that do not affect the S/N ratio are used to adjust the average performance on target. Such parameters are called adjustment factors, and they may be known *a priori* or identified through data analyses. The S/N ratios and details of the design and analyses vary for other parameter-design problems, but the rationale is similar.

The S/N ratio is treated as a response of an experiment that is a measure of the variation within a trial when noise factors are presented. If an outer array is used, the noise variation is forced in an experiment with pure repetitions, so that the noise variations are unforced. The S/N ratio is a response that consolidates repetitions and the effect of noise levels into one data point. A standard ANOVA can be performed on the S/N ratio that will identify minimum factors increasing the average value of the S/N ratio and subsequently reducing variation (Ross 1996).

In order to confirm the assumptions made in the robust design approach, it is recommended to conduct one or more runs at the predicted setting to confirm the experiment and verify that the predicted performance was in fact realized.

4. The sampler tool

The HST or bottom probe set is shown in figure 2. It consists of a cylindrical body, which contains pressure and temperature sensors, a tube connection-detector and the modules to obtain and put away the sample. All of the parts were designed to operate in the presence of H_2S and CO_2. The sampler tool must be connected to a personal computer, in which has been installed the programs to control the tool and the information broadcaster by the sensors. The information can be analysed on the surface in real time when the tool is making measurements of the well fund parameters.

The HST integrates the bottom-hole equipment and consists of the following modules: a muffle camera, an outside sensor module, a storage container, an electronic-control module, and a tube connector locator.

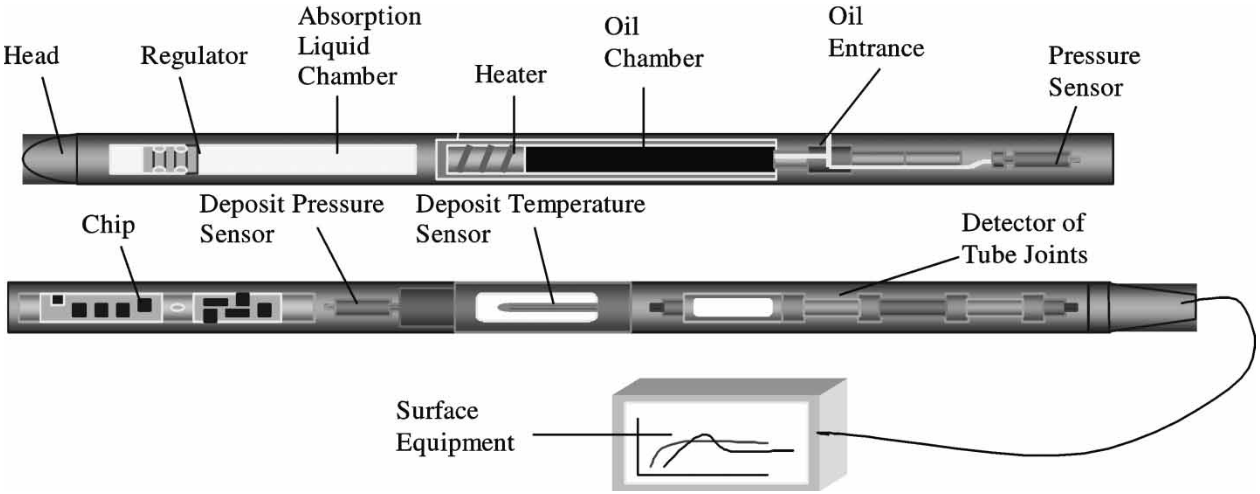

Figure 2. General scheme of sampling system.

The sampler has a 300 ml chamber container for keeping the hydrocarbon fluid. The chamber is supplied by an electric resistance heater, which supplies the necessary calorific energy to maintain the sample at the reservoir temperature. Keeping the pressure and temperature constant allows one to have an adequate analysis of the hydrocarbon samples, and these aspects were taken as the design parameters to develop the tool. The design of the chamber was developed in this paper as a robust design application.

4.1 *General characteristics*

The system presents the opportunity of accomplishing Pressure-Volume-Temperature analysis (PVT) of a liquid hydrocarbon deposit sample with no intermediate pressure–temperature–phase changes. The high-temperature-resistant electronic system allows one to control ($\pm 1°$C, $\pm 1°$F) temperature variations.

The shell, integrated by the sampler and pressure (P) and temperature (T) sensors, can measure the $P - T$ hydrocarbon conditions inside the sampling chamber, using the first sensor group. The second *PT* sensor group registers the well deposit conditions (see figure 2).

The filling of the sampling container is controlled manually using computer software. An electrical motor is used for opening and closing the valve; combined with a mechanism to avoid leaking, it secures the valve either in the open or closed position.

The high-pressure chamber has a piston system that cleans the chamber walls using a volume of octane, assuring the sample free of pollutant substances. The sudden expansion due to pressure deference among the chamber and the reservoir could produce a gas–liquid separation effect; to avoid it, regulation of the hydrocarbon entrance to the chamber is achieved by a damping system based on a floating piston.

After the sampler is extracted from the bottom-hole reservoir it is introduced to a temperature stabilizer. The sampler hydrocarbon chamber is maintained at constant temperature. The transfer of the sample can be accomplished in the laboratory or directly in the field to a high-pressure vessel. Unlike the current sampler tools that require the use of mercury for extracting the sample, the HST system could avoid this absolutely.

An electrical energy supplied by transportation unit is used to maintain the constant temperature. In addition of that, the sampler device is provided by a security battery module. A record of the pressure and temperature parameters of the sample is produced during the transportation, to assure its quality.

5. Robust design in the chamber container case

Figure 2 shows the chamber storage recipient of the HST. The shell is covered by an electric heater and different types of thermal insulators, sustaining minimum heat lost and preserving the fluid in its original state. The chamber container system works as described in the following.

The tool is connected by a 5.690 mm (7/32 inch) single electromechanical cable with the surface control-data-storage module. It is also used for the energy supply feeding the tool electrically. When the tool is introduced in the suitable depth of the well to take the sample, the valve is opened, allowing the sample to enter into the camera. The storage camera has internal pressure and temperature sensors to obtain information about the physical behaviour of the caught fluid. At the time they start to measure the same values of the environment (reservoir conditions) the valve is closed and the sample is caught at the $P - T$ reservoir conditions.

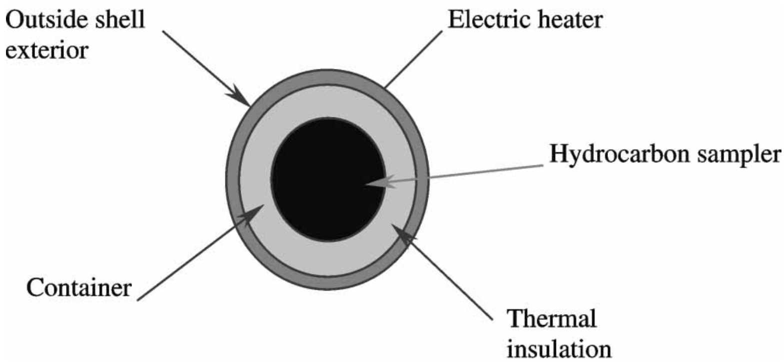

Figure 3. Sampling camera sketch.

The electronic circuit installed in the upper sections of the HST regulates the heater operation. Depending on thermal variations, because of depth, up to 85% of the energy supplied from the surface is lost by the electric resistance of the cable. In order to reduce the heat loss of the sample, the storage camera system was designed like a thermal vessel, with two concentric recipients. Figure 3 shows the arrangement.

An insulating material was placed on the surface of the camera. The external metal shell protects the container and insulates it. The electric heater composed by electric resistances to provide the heat is in the range of 60–120 W. Two electric resistance heaters were connected in parallel, each of them with 60 W of power. When the sampling tool is on the reservoir bottom to obtain a sample, one of the electric resistances is connected, receiving an approximate voltage of 120 V, due to the longitude of the cable that can be up to 9000 m long.

5.1 *Parameter design*

The foremost characteristics of Taguchi experimental design are the use of orthogonal array for designing the experiments and defining the S/N ratio for experimental data analysis. Phadke explains that using the orthogonal table to design experiments enables designers to study the correlation of multiple control factors. To the average value, the variables of quality characteristics are economic and effective (Phadke 1989). Moreover, using the S/N ratio for experimental data analysis enables designers to easily ascertain the optimal parameter combination. This classifies the parameter design into three stages.

5.1.1 Planning the experiment. After collecting data from the problem, the control and noise factors were found. The material of the chamber container, the material of the outside shell, the type of thermal insulation, the electric resistance of the heater, the environment temperature and the type of oil were considered control factors. Tables 1–3 present the factors and the respective levels.

5.1.2 Testing development. The combination of the factor levels is presented in table 4; array L18 was used to develop the experimental procedure. A dummy technique was used to assign the third level to the column to balance the matrix. Figure 4 shows the necessary arrangement to carry out an experimental development, reproducing the nearest operation conditions to achieve an appropriate behaviour analysis of the parameters, as it is indicated in the logical experiments chart. A test bench was built to install special elements and the following

Table 1. The levels and control factors.

Control factor/level	Level 1	Level 2	Level 3
A. Material of the container	Titanium alloy	S. S. Type 316	Titanium alloy
B. Material of the outside shell	Titanium alloy	S. S. Type 17-4Ph	S. S. Type 17-4Ph
C. Type of thermal insulation	Air	Ceramic paper	Vacuum
D. Electric resistance of the heater (Ω)	60	120	Compound (60/120)
E. Temperature of the environment (°C)	25	100	150
F. Type of oil (specific density, g cm^{-1})	0.8892	0.8725	0.925

Table 2. Noise factors.

Control factor/level	Level 1	Level 2
N. Inside temperature behaviour	Heating	Cooling

equipment: pressure sensors with an operating range up to 1055 kg cm^{-2} (15 000 psi), 100 Ω-RTD temperature sensor, 8 Ω m^{-1} nichrome tape, an electric heater with capacity of heating up to 300°C, temperature data storage, a manual hydraulic pump, M-100 silicon oil, a mechanical vacuum pump, an electric supplier source, Teflon cables, high-pressure stainless steel connectors as well as an electronic regulator for voltage control.

Table 5 establishes the order in which to carry out the experimentation. Figure 4 shows the system used for the first experiment. The sampler container and the external case were

Table 3. Signal factor.

Factor	Level
M. Enough energy to feed the heater on the bottom hole	Heat add to the tool container owing to lost

Table 4. Experimental array.

	Column and factor							
Experiment number	1e	2A	3B	4C	5D	6E	7e	8F
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

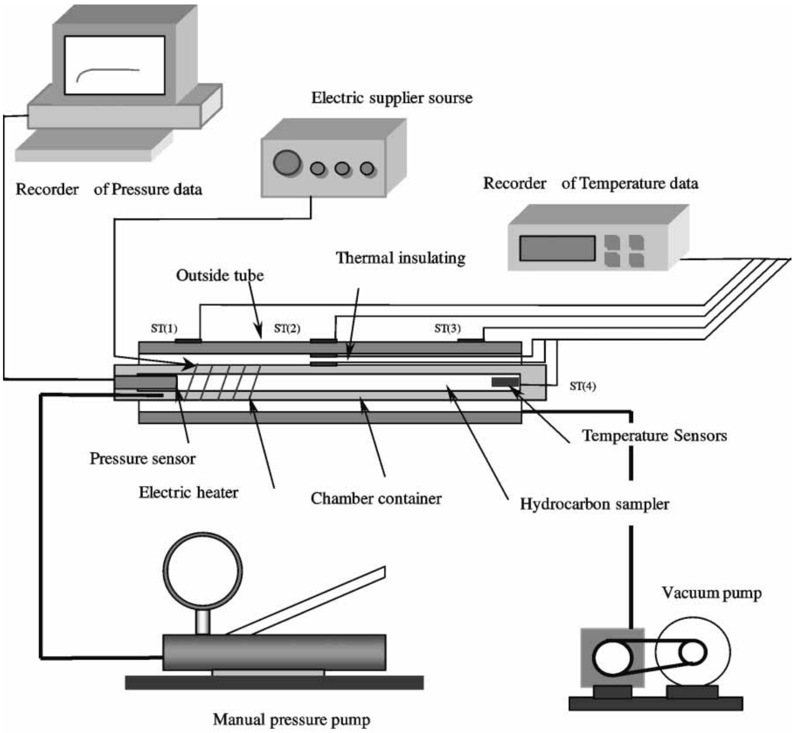

Figure 4. Whole system used to carry out the experiments.

Table 5. Logical experiment table.

Experiment number	A Material of the container	B Material of the outside shell	C Type of insulation	D Electric resistance of the heater (Ω)	E Working temperature (°C)	F Type of oil
1	Titanium alloy	Titanium alloy	Air	60	25	1
2	Titanium alloy	S.S. type 17-4 Ph	Ceramic paper	120	100	2
3	Titanium alloy	S.S. type 17-4 Ph	Vacuum	Compound	150	3
4	S.S. type 316	Titanium alloy	Air	120	100	3
5	S.S. type 316	S.S. type 17-4 Ph	Ceramic paper	Compound	150	1
6	S.S. type 316	S.S. type 17-4 Ph	Vacuum	60	25	2
7	Titanium alloy	Titanium alloy	Ceramic paper	60	150	3
8	Titanium alloy	S.S. type 17-4 Ph	Vacuum	120	25	1
9	Titanium alloy	S.S. type 17-4 Ph	Air	Compound	100	2
10	Titanium alloy	Titanium alloy	Vacuum	Compound	100	1
11	Titanium alloy	S.S. type 17-4 Ph	Air	60	150	2
12	Titanium alloy	S.S. type 17-4 Ph	Ceramic paper	120	25	3
13	S.S. type 316	Titanium alloy	Ceramic paper	Compound	25	2
14	S.S. type 316	S.S. type 17-4 Ph	Vacuum	60	100	3
15	S.S. type 316	S.S. type 17-4 Ph	Air	120	150	1
16	Titanium alloy	Titanium alloy	Vacuum	120	150	2
17	Titanium alloy	S.S. type 17-4 Ph	Air	Compound	25	3
18	Titanium alloy	S.S. type 17-4 Ph	Ceramic paper	60	100	1

Type of oil: 1, 0.8892 g cm^{-1}; 2, 0.8725 g cm^{-1}; 3, 0.925 g cm^{-1}.

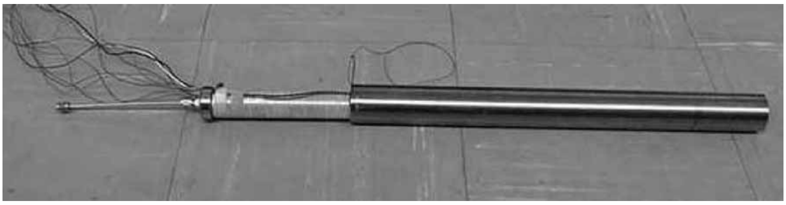

Figure 5. The heater and the container.

manufactured from titanium alloy. Air was used to insulate the annular space (figure 3). A 60 Ω heater was selected, the atmospheric temperature was 25°C, and a slight oil sample of 0.8892 g cm^{-1} was also used. Consequently the first experiment had the combination A1, B1, C1, D1, E1, F1. Phandke establishes diverse approaches to conduct the matrix of experiments; a common practice is the random development, taking care that all the parameters arrive in their original states. In this case, the operations with temperature should be considered thoroughly to avoid interrelations that would complicate the development of the experiment – the case of a new factor of noise would be presented and could enter inside the analysis parameters; however, it is not advisable (Phadke 1989). In this case if the experiment requires 25°C of temperature and the last experiment has ended with 100°C, it is necessary to carry the system to the indicated temperature in the logical chart of experiments. This provided us with real data in the optimization of the factors affecting the sensibility of the design. Figures 5 and 6 show the equipment used to make the experiments.

5.1.3 Data analysis. According to the purpose of the S/N ratio, two classifications exist: dynamic, and static (not dynamic). The dynamic S/N ratio specifies that an input signal exists, identified by the real value of the event to measure, and the output is the direct result of the input; this can be read directly from the instrumentation used. Yuin Wu and Wu (1999) show that the relationships of the dynamic S/N ratio type are used to improve the robustness of the product function in an output range. The static S/N ratio (non-dynamic) is used to improve the robustness of the objective function for the certain output, instead of for the whole range.

There are two aspects in the S/N relations: to reduce the variability, and to adjust the measure to the objective value.

The static problems can be classified by the nature of the quality characteristic, remembering that the prospective answer is called a quality characteristic and is the objective for

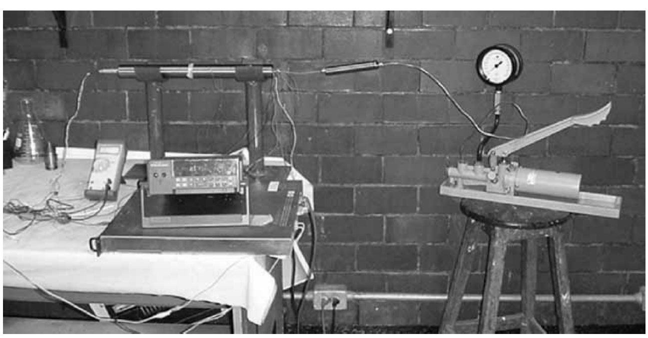

Figure 6. The whole system of the experiment.

Table 6. Heating phase data.

Experiment number	Diference of temperature (heating phase, °C)					Heating time (min) (°C)		Index of heating (°C min^{-1})
1	62	87	74	55	42	95	(de 28.04 a 93.27)	0.686
2	2	2	2	2	2	78	(de 29.5 a 118.55)	1.142
3	67	63	73	84	70	75	(de 19.82 a 119.74)	1.332
4	24	26	25	27	25	60	(de 24.21 a 107.73)	1.392
5	50	49	46	38	38	105	(de 29.43 a 136.48)	1.019
6	71	69	75	70	64	50	(de 22.35 a 105.97)	1.672
7	30	40	40	37	34	75	(de 32.6 a 137.22)	1.394
8	67	71	74	67	69	45	(de 26.91 a 101.49)	1.657
9	28	33	30	27	23	90	(de 27.4 a 101.54)	0.820
10	52	66	65	54	39	97	(de 27.64 a 97.12)	0.716
11	43	48	52	48	44	80	(de 26.76 a 122.67)	1.198
12	46	49	50	48	47	25	(de 30.86 a 100.98)	2.804
13	27	31	25	25	24	80	(de 26.4 a 100.67)	0.928
14	67	69	64	64	63	55	(de 23.16 a 103.11)	1.453
15	26	26	28	30	27	43	(de 38.2 a 129.6)	2.125
16	87	88	87	75	70	85	(de 24.55 a 103.71)	0.931
17	30	33	36	34	31	60	(de 26.58 a 98.8)	1.203
18	33	37	34	30	29	60	(de 25.59 a 103.23)	1.294

improvement. For the static focus there are four types of application: nominal-the-better (NB), lower-the-better (LB), higher-the-better, and operative window non-dynamics.

The main problem could be to consider a static type S/N ratio (non-dynamic) of the type HB, because it is required that the signal response of the system is translated to a bigger temperature difference among the container (T_c) and the exterior temperature (T_e); both parameters describe the thermal behaviour of the system – being positive if $T_c > T_e$ and being negative when $T_c < T_e$, depending on the operation phase. However, if the problem is analysed estimating the quantity of heat that is transferred outside, the most convenient way is to consider the problem as a S/N type LB. Charts are presented to show the position of the experiment, the results and the analysis (see tables 6 and 7).

The S/N ratio is given by the equation:

$$\eta = -\log_{10}\left[\frac{1}{N}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{1}$$

The main group of η for the experimental region defined by the factors levels (see table 8) is:

$$m = \frac{1}{18}\sum_{i=1}^{18}\eta_i \tag{2}$$

$$m = \frac{1}{18}[\eta_1 + \eta_2 + \cdots + \eta_{18}] \tag{3}$$

where m is a balance of the main group of the experimental region.

The effect of a factor level is defined as the deviation that the factor causes upon the total average. Using equation (4) we can evaluate the effect of the material of the container A3 on the system. The average of the S/N ratio in this experiment is denoted by m_{A3}:

$$m_{A_3} = \frac{1}{6}[\eta_7 + \eta_8 + \eta_9 + \eta_{16} + \eta_{17} + \eta_{18}] \tag{4}$$

Table 7. Cooling phase data.

Experiment number	Diference of temperature (cooling phase, °C)					Cooling time (min) (°C)		Index of cooling (°C min^{-1})
1	34	41	43	41	39	95	(de 93.27 a 42.58)	0.53
2	21	14	9	6	5	115	(de 102.8 a 38.92)	0.55
3	34	38	41	45	41	145	(de 116.59 a 39.51)	0.53
4	15	16	16	15	16	105	(de 100.86 a 41.21)	0.56
5	27	27	25	22	20	65	(de 106.61 a 55.41)	0.78
6	64	58	53	49	12	140	(de 105.97 a 40.8)	0.46
7	21	25	24	22	19	123	(de 104.14 a 35.57)	0.55
8	57	52	44	40	37	100	(de 101.49 a 41.1)	0.60
9	16	18	19	16	15	80	(de 100.35 a 47.25)	0.66
10	25	25	29	27	23	105	(de 95.10 a 48.13)	0.45
11	20	20	22	22	19	75	(de 103.94 a 47.28)	0.75
12	45	44	44	42	38	135	(de 100.9 a 36.27)	0.47
13	23	19	17	15	14	110	(de 100.85 a 39.64)	0.55
14	62	57	56	50	45	155	(de 100.83 a 40.5)	0.39
15	27	25	25	25	39	35	(de129.2 a 89.9)	1.12
16	35	31	29	25	22	90	(de 101.43 a 39.35)	0.69
17	29	25	21	19	17	90	(de 98.8 a 40.31)	0.65
18	17	18	17	16	13	100	(de 103.6 a 40.96)	0.62

Then, the effect of the material of the container A3 is $(m_{A3} - m) = 0.05\,\mathrm{dB}$, which means that this factor has a little influence in the variability of the heat process in the system. The complete variance analysis is presented in table 8.

From figure 7, the optimal factor of combination levels for the experiment is A2, B3, C3, D1, E1 and F3; factors C, E and F, have the biggest influence in the process.

Table 8. Computation and S/N ratio of the experiment.

Experiment number	Experimental conditions								Temperature behaviour (FR)										η (dB)	μc (°C)	μe (°C)	μ (°C)
	1e	2A	3B	4C	5D	6E	7e	8F	Nh					Nc								
1	1	1	1	1	1	1	1	1	62	87	74	55	42	34	41	43	41	39	33.25	64	39.6	51.8
2	1	1	2	2	2	2	2	2	2	2	2	2	2	21	14	9	6	5	8.73	2	11	6.5
3	1	1	3	3	3	3	3	3	67	63	73	84	70	34	38	41	41	41	33.61	71.4	39	55.2
4	1	2	1	1	2	2	3	3	24	26	25	27	25	15	16	16	15	16	25.46	25.4	15.6	20.5
5	1	2	2	2	3	3	1	1	50	49	46	38	38	27	27	25	22	20	29.36	44.2	24.2	34.2
6	1	2	3	3	1	1	2	2	71	69	75	70	64	64	58	53	49	41	35.31	69.8	53	61.4
7	1	3	1	2	1	3	2	3	30	40	40	37	34	21	25	24	22	19	28.41	36.2	22.2	29.2
8	1	3	2	3	2	1	3	1	67	71	74	67	69	57	52	44	40	37	34.45	34.8	46	40.4
9	1	3	3	1	3	2	1	2	28	33	30	27	23	16	18	19	16	15	26.07	28.2	16.8	22.5
10	2	1	1	3	3	2	2	1	52	66	65	54	39	25	25	29	27	23	30.22	55.2	25.8	40.5
11	2	1	2	1	1	3	3	2	43	48	52	48	44	20	20	22	22	19	28.47	47	20.6	33.8
12	2	1	3	2	2	1	1	3	46	49	50	48	47	45	44	44	42	38	33.04	47.4	42.6	45
13	2	2	1	2	3	1	3	2	27	31	25	25	24	23	19	17	15	14	26.01	26.4	17.6	22
14	2	2	2	3	1	2	1	3	67	69	64	64	63	62	57	56	50	45	35.29	65.4	54	59.7
15	2	2	3	1	2	3	2	1	26	26	28	30	27	27	25	25	25	39	28.68	27.4	28.2	27.8
16	2	3	1	3	2	3	1	2	87	88	87	75	70	35	31	29	25	22	31.25	81.4	28.4	54.9
17	2	3	2	1	3	1	2	3	30	33	36	34	31	29	25	21	19	17	27.96	32.8	22.2	27.5
18	2	3	3	2	1	2	3	1	33	37	34	30	29	17	18	17	16	13	26.08	32.6	16.2	24.4

*Factors that were used to estimate the error of the mean square.

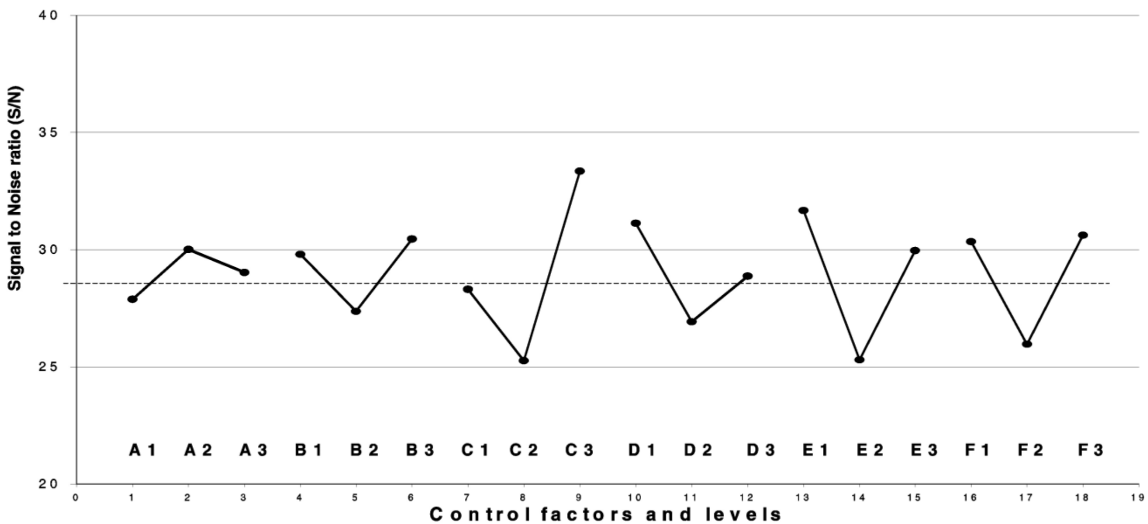

Figure 7. Response graphs of the experiment.

Through a S/N ratio analysis, the factors effect was obtained. However, we still did not have any information concerning the overall significance of their effects. The purpose of the ANOVA is to study the significance among the factors. Therefore, we have to conduct the ANOVA to determine that significance of each factor. Table 10 presents the results of the ANOVA in the experiment.

6. Experimental results

The objective of the analysis of the heating system in the chamber container was to obtain the influence of each parameter as well as the optimum level to diminish the transference of heat to build an optimum system. It was possible through evaluating the difference between temperatures; the HB approach for a non-dynamic process was used, where '$-$ log' is a falling monotonous function that implies we should maximize the value of the S/N ratio, reducing the influence of noise factors. Table 9 presents the response of the factors in the experiments.

Analysing tables 9 and 10, the factors C, E and F have a bigger effect. In consequence, the best option to build the container is A2, the best material for the external shell is B3, the best

Table 9. Response tables of the experiment.

Factor	Average of η (dB) 1	2	3	Effect between averages of η
A. Material of the container	27.8867	30.0183	29.0366	2.13
B. Material of the outside shell	29.1	27.3767	30.465	3.08
C. Type of thermal insulating	28.315	25.2717	33.355	8.08
D. Electric resistance of the heater	31.135	26.935	28.8717	4.2
E. Temperature of the environment	31.67	25.3083	29.9633	6.36
F. Type of oil captured	30.34	25.9733	30.6283	4.66

Table 10. ANOVA in the experiment.

Factor	Average of η (dB) 1	2	3	Degrees of freedom	Sum of squares	Mean square	F	Contribution (%)
A. Material of the container of the container	27.8867	30.0183	29.0366	2	13.6594*	6.8297	0.3221	2.19
B. Material of the outside shell outside shell	29.1	27.3767	30.465	2	28.7412*	14.3706	0.6778	4.48
C. Type of thermal insulating thermal insulating	28.315	25.2717	33.355	2	200.0060	100.003	4.7170	32.12
D. Electric resistance of the heater	31.135	26.935	28.8717	2	53.0267	26.5013	1.2500	8.52
E. Temperature of the environment	31.67	25.3083	29.9633	2	130.1061	65.053	3.0685	20.90
F. Type of oil captured	30.34	25.9733	30.6283	2	81.6402	40.8202	1.9254	13.11
Error				5	115.4812	23.0962		18.68
Total				17	622.661			100
(Error)				(6)	(42.4006)	(21.2003)		

*Factors that were used to estimate the error of the mean square.

type of insulating is C3, and the system operates optimally in an external temperature similar to E1, using a heater of the type D1 as well as that the system operates optimally with oil type F3.

From the experiment orthogonal array, the combination A2, B3, C3, D1, E1, F3 maximizes the relationship of the S/N ratio. The following operations with the sum of squares for the experimental results provided information about the predicted performance of the best combination of parameters for the system.

The E and F factors were considered a noise factors; however, they were included inside the array of experiments as control factors to analyse their effect on the system. Table 9 shows that both factors were important for the system, so a more careful analysis was necessary to consider their effects in the system at the detailed design state. The factor D is also a very important parameter (it has a moderate influence on the S/N ratio) because this factor could improve the system if it is set on the D3 level.

In table 10, using ANOVA, the biggest contribution to the total sum of squares was 32.12%, the second place was for E, with 20.90% of the total of the sum of squares. These results also showed that factor E, external temperature, has a great influence in the relationship of the S/N ratio.

The graph in figure 8 shows an experiment using the optimum conditions; there is an appreciable difference between the temperatures outside and inside the tool. The electric energy to feed the HST and the container was reduced; now it is possible to preserve the temperature using 0.700 A, 28% less than the previous design. Reducing the temperature losses of the container helped to electrically control the heater, and consequently the thermodynamic variations of the sample, keeping it in a permanent simple phase.

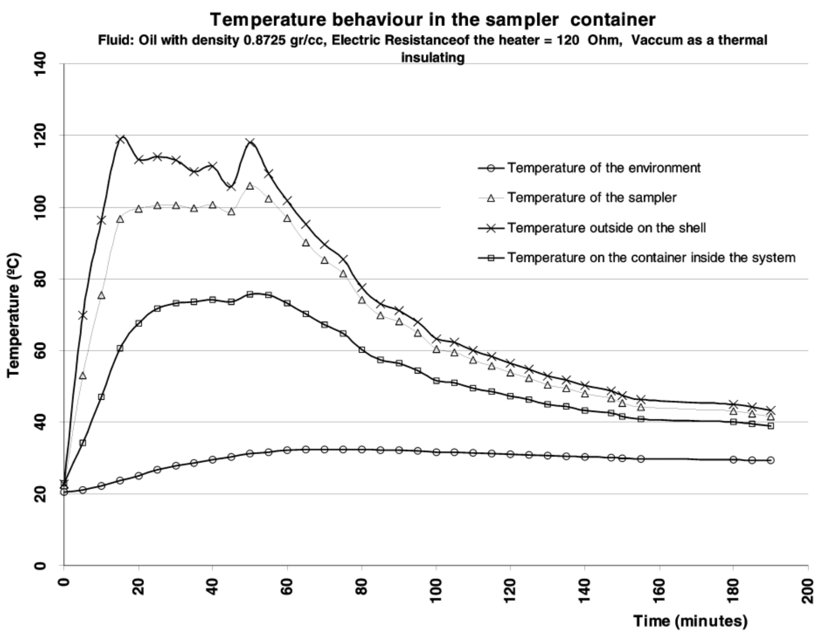

Figure 8. Temperature behaviour in the sampler container with optimum parameters.

Table 11. Factors with bigger influence in the variability of the system.

Factor of control	Optimum level
A. Material of the container	S. S. Type 316
B. Material of the external shell S. S. Type 17-4Ph	
C. Type of insulating	Vacuum
D. Electric resistance of the heater compound (60 and 120 Ω)	
F. Type of oil	$0.925\ \mathrm{g\,cm^{-1}}$ (heavy oils)

7. Conclusions

The results of the research up to this point show that robust design was an effective method for finding the best combinations of parameters. Hence a solution could be configured based on the configuration pointed out in table 11, to design and optimize some parts of the sampler tool. Currently, a prototype of the storage container is under construction for testing first at the laboratory level, and then in oilfields. Due to material availability we have changed the titanium alloy in the prototype for a stainless steel type 17-4 PH, making the corresponding correction in the performance prediction. The main problem was solved translating the result in a system with low energy losses, so that the combination of the best parameters made it possible to redesign and build an optimized storage container.

Before these results, a prototype of the storage container was proven using titanium alloy, which has a more minor coefficient of thermal conductivity than stainless steel. However, stainless steel type 17-4 PH has good mechanical properties, and cost, to withstand the high pressure in the reservoir, and also withstands corrosion.

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