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Determining the Optimum Descaling Requirement of Utilising Multiple Flat Fan Nozzles in cleaning Paraffin Inflicted Petroleum Production Tubing

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Abstract

Despite the recent detailed results obtained from numerous researches in the utilisation of hydraulic descaling techniques that elaborates the erosion behaviour of multiple high-pressure flat fan nozzles in descaling petroleum production tubing's embedded with different types and shapes of scale deposits. Through the adoption of both hydrodynamic connected parameters like injection pressure and numbers of nozzles and also the non-hydro connected parameters like stand-off distance, nozzles arrangements and chamber pressure. That lead to achieving the main research goal of enhancing the removal capacity via the permutation and combination of the aforementioned descaling parameter. Theirs still need of determining the best combination of descaling parameters required for effectively and efficient descaling of each type of scale deposit. Thereby, developing an operational guide for removing each scale type and shape when utilising multiple high-pressure nozzles and other descaling parameters will be very valuable for the petroleum production technologist handling the flow assurance of a scale inflicted well. This novel experimental scale removal technique utilizes multiple high-pressure spray of up to 10MPa and low flow rate of 12 l/m from multiple flat fan nozzles of different arrangement and stand-off distance. That is housed in a constructed simulated production tubing chamber with vacuum and compression capacities to remove constructed wax deposit (paraffin) of different shapes signifying different growth stages of paraffin in production tubing. Generally, the performance of each or combination of the descaling parameters during the experiment depends on the shape and type of the scale deposit in question, most especially the chamber air concertation and nozzles arrangements. Also, the amount removed of all the respective scale deposit was found to increase with increase in injection pressure and reduction in number of nozzles.

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Likewise, the effect of stand-off distance toward the erosion rate of all the respective descaling candidates was found to reduce with increase in downhole jetting position, even though could be compensated with the right choice of nozzles arrangement.

KeyWords: Scale removal; multiple nozzles; high-pressure water spray; flat-fan nozzle.

1. Introduction

Until date, scale deposition in petroleum production tubing remains the biggest threat to flow assurance. This is because, production tubing serves as both the main production conduit as well as the only access for remedial and maintenance programs such as well logging and the rest [46]. Additionally, petroleum products are produced and transported from the reservoir to the surface via pipelines and other flow channels [25, 26] that are consequently, prone to scale deposition since they are constantly in contact with produced water during production from the field [18,17 & 30]. Among all the petroleum production associated problems, scale deposition in petroleum production tubing remains the biggest petroleum production technologist nightmare due to its operational, technical and financial implications that usually, require quick, safe and costly interventions to remediate [42]. In addition, to the inability to develop universal treatment for all type of scale deposit, formations and wells create limitations for the selection of tools and techniques for oilfield descaling operations up-to-date [16]. Scholars like [4 & 21] believes such types of operations are mostly governed by the knowledge of the type, quantity, texture, composition and location of the scale to be remove.

Although, scale deposition process is mainly attributed to mixture of incompatible waters during secondary oil recovery, changes in thermodynamic conditions in the tubing during production, poor planning and inadequate incorporation of scale control strategies into the field's assets management cycle [14]. Notwithstanding, scale depositions may occur either before the deployment of inhibition or at the expiration of the inhibition [35], limiting the treatment options to confrontation emergency (cure) removal measures that need to be done in a fast and safe manner.

Many reservoir minerals, depending on the reservoir chemical characteristics and oil recovery techniques utilized like water flooding enhanced oil recovery promote the deposition of inorganic scales [5] such as calcium and carbonate scales, that are responsible for oil field scale deposits on production tubing [13]. However, calcium carbonate, calcium sulfates and barium sulfates are the most predominant inorganic scale deposit [47]. In addition to, organic scales such as aliphatic and paraffin attributed to dynamic nature of hydrocarbon production process as a result of physiochemical and thermodynamic changes in properties of the produced fluid (volume, temperature, pH and pressure), which can deposit at any part of the production system [7]. Nevertheless, other important scale deposition influencing factors such as produced water properties, CO_2 liberation, nature of the surface, hydrodynamics of the system and flow regime [22] should not be underrated. Nonetheless, most times organic scale deposition is directly connected to the heavy crude production nature of a field that is somehow globally distributed [12] as shown in Figure C1 of [45]. Paraffin scale deposits predominate most forms of scale deposition and are the most encountered in production tubing due to the physicochemical changes of the produced fluid. Moreover, a previous study, according to [36] characterized paraffin as having a melting point of 51.4 °C, bulk density of 900 kg/m3, thermal conductivity of 0.22 W/mK and latent heat of 245.1 J/g and it is also insoluble in water but soluble in benzene and some esters. However, combination of both organic and inorganic scale deposit can simultaneously occur at same location like the case of Saudi Aramco wells reported by [6] among many.

Many inefficient and unsafe scale removal techniques like the destructive mechanical method (such as explosives) [10], the use of aggressive chemical solutions like HCl [20], rig work over to replace the tubing and even differing of production [38] were unsuccessfully tried in the past [19]. Although, in recent times, the mechanical approach of utilising high-pressure water jetting techniques has been widely accepted by the multinational Oil and Gas Industry [8], despite been associated with back pressure challenges (like cavitation). The introduction of sand particles in the descaling fluid (slurry or abrasion) by [9] seems to improve the performance, however, but at the expense of the integrity of the well completions. Similarly, the replacement of sand with sterling beads by [23] was impressive but with more environmental complexity. While the recent introduction of the single high pressure aerated flat fan spray approach by [3] was successful. Although, its characterized by poor scale coverage and high rig time.

2. Experimental *Procedure*

2.1 Method

The preliminary descaling experiment are conducted outside the descaling chamber, in preparation of descaling experiments [39] by: Firstly, designing, constructing and assembling of the upgraded descaling rig including the descaling chamber (ambient, compressed and vacuumed condition) in simulation of ideal descaling conditions which is pictorially presented in Figure C2 of [45]. Secondly, designing/ fabricating of wax scale moulder (see C-12 of 45) and its further utilization to produce soft scale samples candidate of different sizes and shape that can simulate different stages of scale growth in production tubing. Thirdly, by chemical characterization of the constructed soft scale sample to ascertained their similarities in chemical properties with the typical oil field paraffin deposit using NMR & FTIR techniques as detailed in [39]. Finally, determining the optimum descaling requirement in terms of hydrodynamic connected parameters like injection pressure and numbers of nozzles and also the non-hydrodynamic parameters like stand-off distance and nozzle configuration for the effective scale removal of different scale deposit shapes in petroleum production tubing in different chamber pressure.

2.1. Materials

Oilfield wax were simulated by fabricating them from off-the-shelves candles which were melted and casted in a convertible mould (as shown in C-12 of 45) to establish the desired shape and type of the wax for the experiment as graphically elaborated in Figure 2.1. Also, a combination of Nuclear Magnetic Resonance (NMR) and Infrared analysis (FT-IR) respectively were utilized in investigating the chemical similarities of the constructed wax from household candles to real oilfield paraffin deposit as stated in the work of [40, 41].

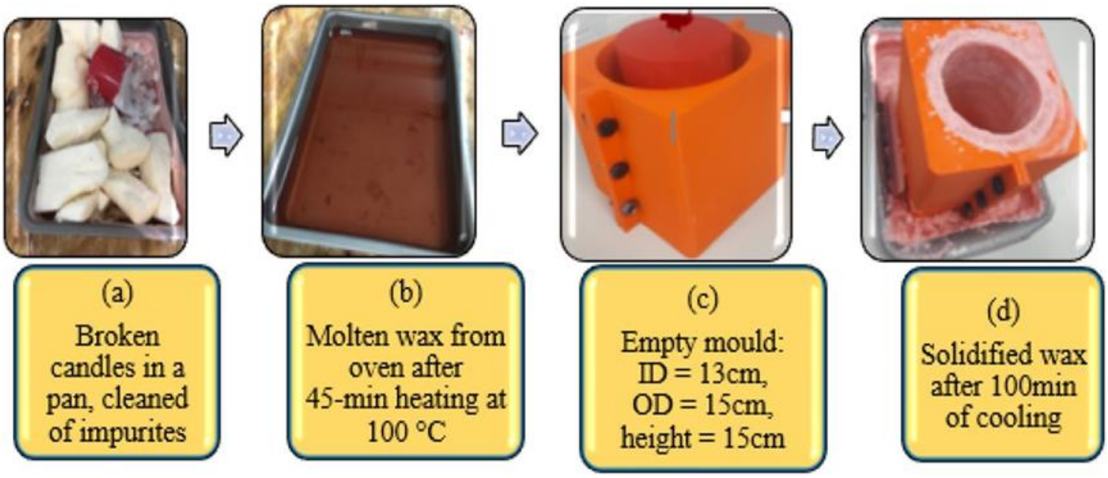


Figure 2.1: Graphical Preparation of wax scale samples (a) Candle, (b)melted wax (c) caste**[40]** [wax and (d) wax sample after cooling **[**40].

This novel scale removal experimental technique utilizes a multiple nozzle header with three (3) to five (5) flat fan nozzles. These nozzles were arranged in different orientations and stand-off distances for a parametric sensitivity analysis on descaling performance. The experiment was conducted at 4.8, 6.0 and 10MPa injection pressure for 3 minutes to remove paraffin scale deposits in the production tubing at different growth stage as shown in Figure 2.2

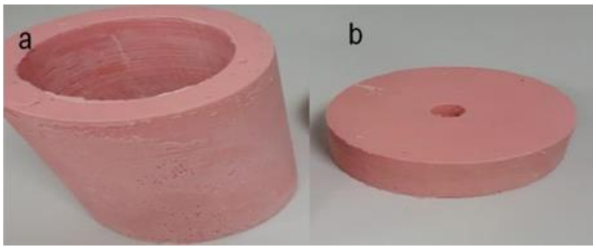


Figure 2.2: Constructed softs Scale (a)hollow shaped,(b)solid[39] shaped[39].

The descaling rig, illustrated in **Figure 2.3,** comprises of a descaling chamber housing the scale deposit and a multiple nozzle header that is fed from the high-pressure water pump connected to a compressed air system and a vacuum pump. Also, both streams are regulated from a control board to achieve the desired chamber air pressures and jet impact pressures to remove paraffin deposit of different shapes.

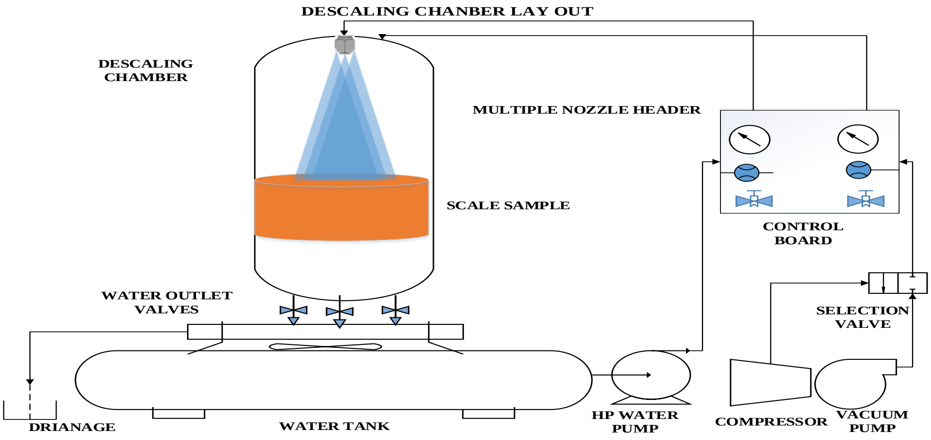


Figure 2. 3: Descaling rig set-up [39].

So also, in order to investigate the most effective chamber pressure requirement of cleaning scale deposit of different shapes. Some vital components of the experimental set-up, like the HP, compressed air supply and suction pumps are shown in **Figure 2.4** were added onto the constructed chamber**.** The compressed chamber option was achieved by introducing 0.2MPa compressed air into the chamber whilst simultaneously spraying water at high injection pressure or suctioning the chamber by -0.08MPa respectively.

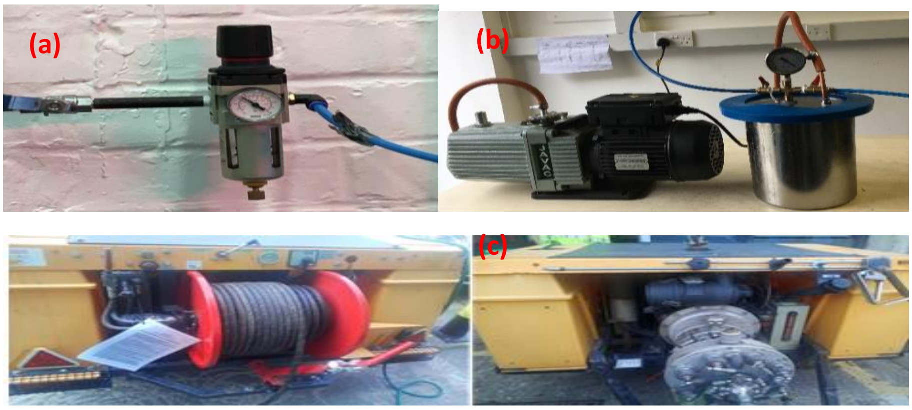


Figure 2.4: Descaling rig components, (a) Compressed air system, (b) Vacuum pump & (c) high pressure water pump [39].

All the respective descaling experiments were performed by fitting the multiple high-pressure headers with the desired nozzle configurations and setting them at 25mm, 50mm or 75mm stand-off distance (the vertical distance from the tip of the side atomizer/nozzles to the face of the scale sample), and then pumping fresh solid free water at different pressures as schematically shown in **Figure 2.5, 2.6** and graphically illustrated in **Figure 2.7**. This is done to find the most effective distance for removing different types and shapes of scale deposits of different growth stages.

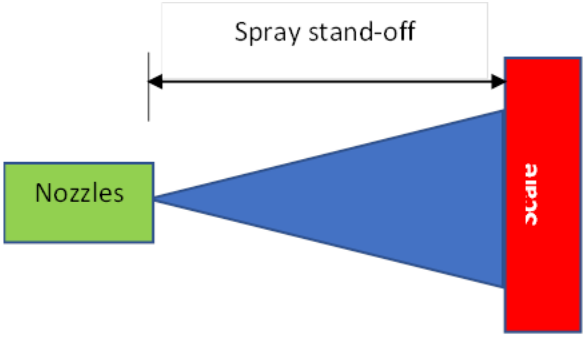


Figure 2. 5: Schematic spray stand-off of single Nozzles [40].

Multiple-Spray stand-off

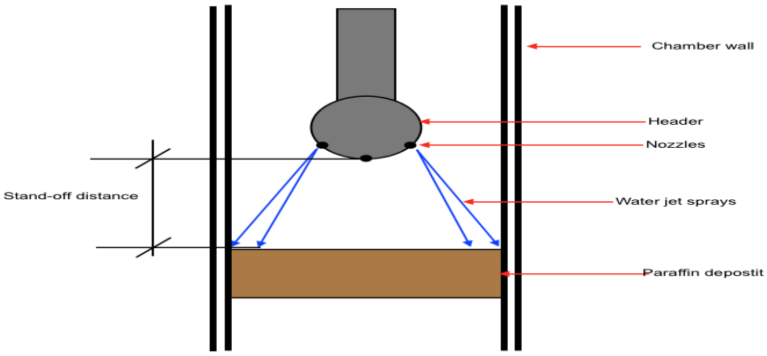


Figure 2. 6: Stand-off distance for multiple Nozzle Header [42].

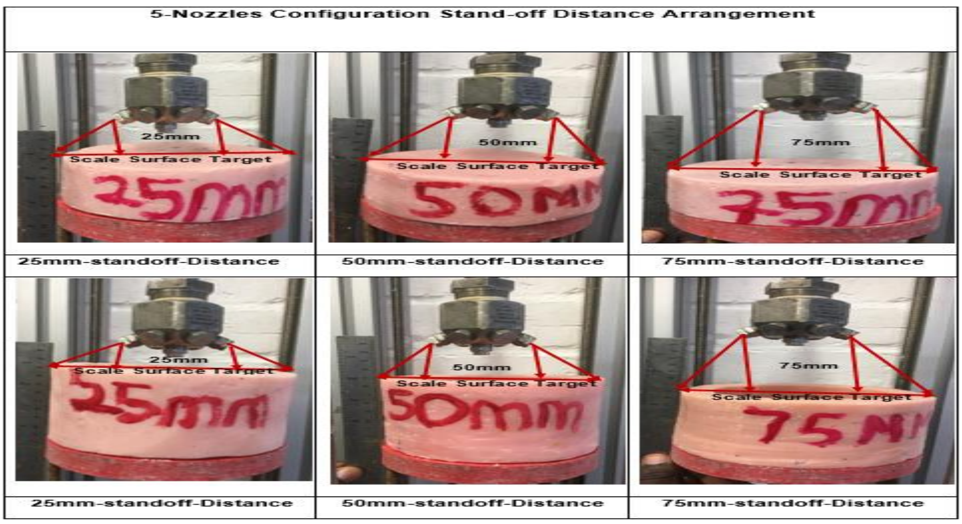


Figure 2. 7: Stand-off distance arrangement [39].

The nozzle header configuration comprising of different nozzle arrangements is shown in **Figure 2.8**. The configurations were achieved by fitting in 3, 4 or 5 orifices/nozzles into the seven (7) header nozzles sockets required to achieve desired nozzles arrangements and blocking the remaining undesired sockets with plugs or “blinds”. The three main nozzle arrangements were in the form of; non-centre nozzle (NCN), centre nozzle (CN) and centre nozzle overlap (NCO) arrangements as shown in **Figure 2.8**. The primary purpose of altering the nozzle arrangement during the experiment was to find an effective arrangement for cleaning paraffin deposits of different shapes.

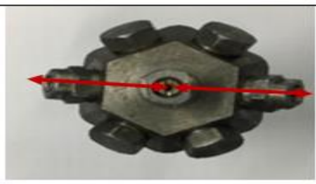
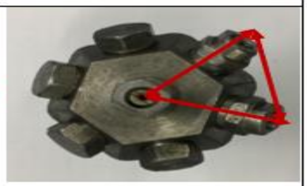
No of Nozzles	Header/Nozzle Configuration		
	Non-Centre Nozzle Configurations (NCN)	Centre Nozzles Configurations (CN)	Centre Nozzle Overlap Configurations (CNO)
5	 Pentagon	 Envelope	 Trapezium
4	 Rectangle	 Pyramid	 Kite
3	 Triangle	 Diagonal	 Right-angled

Figure 2. 8: Header and nozzles arrangements for 3 nozzles at NCN, CN &CNO arrangements [39]**.**

2.3. Procedure

i. The weight of each sample was measured using an electric weight balance and its picture was taken with a still camera before and after the experiment.
ii. The desired nozzle arrangement amongst NCN, CN and CNO was generated by fitting the required nozzles and blocking the undesired with blank plugs onto the nozzle header.
iii. The scale samples were appropriately placed on the scale sample holder and secured in the right position in the descaling chamber.
iv. The desired stand-off distance amongst 25mm, 50mm and 75mm were achieved through the selection and combination of the right sizes of the sample packers.
v. The desired chamber air pressure (ambient, compressed or suctioned air) was ensured through the utilization of an isolation/selection valve that was connected to both the compressed air channel and vacuum pump via the controlled board.

vi. The high-pressure water pump was turned on and carefully throttled to the desired injection pressure of 4.8, 6.0 or 10MPa.

vii. The regulatory valves of the control board were utilized to control and monitor the pressure gauges and flow meters along the waterline and air on the board and, also on top of the rig for corresponding experimental pumping and air requirement.

viii. The high-pressure water pump was stopped when the stop-watch reads three (3) minute descaling time at the desired chamber pressure.

ix. The selection/isolation valve was closed and the chamber pressure feed i.e. compressed air or vacuum pump was turned off immediately after the 3-minute descaling time was achieved.

x. The descaled samples were weighed, and their pictures were taken after drying for 12 hours including the broken samples collected through the two sieves below the packers

xi. Steps i to x were repeated for desired standoff distance of 25mm, 50mm and 75mm, respectively.

xii. Steps i to xi were repeated for 4.8, 6.0 and 10MPa injection pressure respectively.

xiii. Step i to xii of the experiment were repeated for desired nozzles arrangement (NCN, CN & CNO) respectively.

xiv. Step i to xiii above were applied and repeated for various scale shapes (hollow and solid deposits).

3. Results and discussion

3.1. Scale Deposit Characterization

As detailed in the **[39]** on how the nuclear magnetic resonance spectroscopy technique was utilised in investigating the presence of the chemical properties of typical oil field scale deposits (paraffin) in the constructed soft scale samples. The spectra of the 1H NMR in **Figure 3.1** proofs the presence of Olefinic protons between δ= 0.5 ppm – δ= 1.5ppm are characteristics of hydrogens on CH, CH2 and CH3 groups. This region of the peaks corresponds with spectra reported in the literature **[29]**. As mentioned earlier in **[39]**, singlet at δ = 0.0 ppm is assigned for TMS and mainly used as a calibration peak. The singlet peak at the extreme (δ = 7.278 ppm) is assigned to the deuterated chloroform (CDCl3) solvent which was used to dissolve the sample. The characteristic signals of the spectra confirm the presence as saturated hydrocarbon (signals in the up field). No peaks were observed in the aromatic region of the spectra between δ = 7.0 ppm and δ = 8.0 ppm.

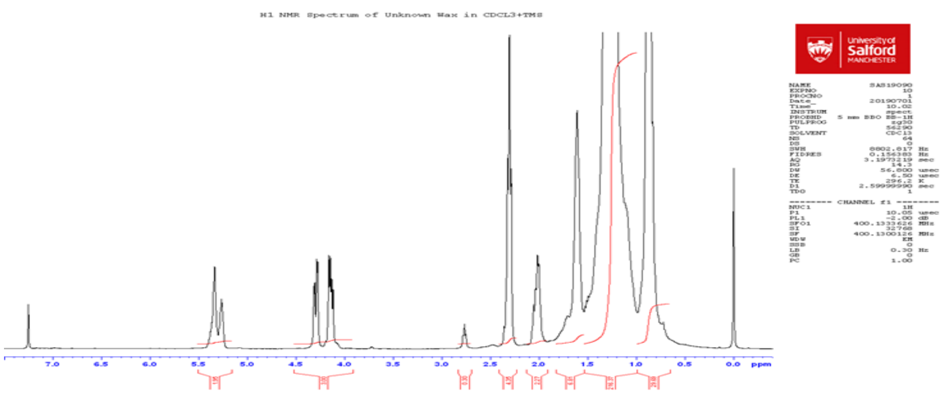


Figure 3. 1: NMR analysis results [39].

The constructed wax scale deposit was further subjected to Infrared Spectroscopy Analysis for verification of the NMR result and re-affirmation of its chemical representativeness of the oil field scale deposit (paraffin). As discussed in the methodology chapter of the work [39], the results generated by Thermo Scientific Nicolet iS10 for the prepared wax sample, were revalidated. This is done through superimposing the results with the paraffin flakes results from the system in-built archived (database) which seems to share same functional groups in Figure 3.2a. Also, both spectrums coincide by revealing similar fingerprint and bands for a functional group of paraffin. Furthermore, FT-IR in Figure 3.2a, the absorption peaks between 2900 cm-1 and 2800 cm-1 is assigned for stretching and vibrations of CH2 and CH3, which confirms the nature of paraffin present in the sample as aliphatic [24]. The absorption peaks also matched with those retrieved from National Institute of Standard and Technology (NIST) database of FT-IR spectra. Likewise, for more validation and confirmation, the soft wax sample spectra were superimposed and compared with the results from the liquid paraffin confirmatory test as explained in Section 4.2.2.2 of [39] and presented in Figure 3.3b, were both the spectrum of the soft wax and liquid paraffin share the same peaks and bands of paraffin functional group.

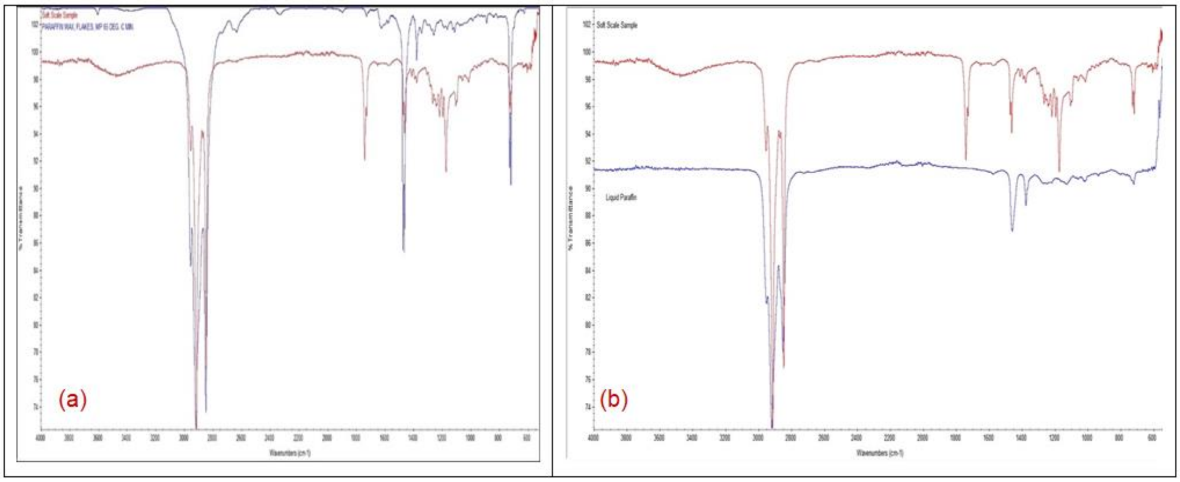


Figure 3.2: Infrared analysis results compared to (a) paraffin flakes from NIST data base (b) liquid paraffin sample [39].

3.2. Nozzle Configuration

For the purpose of familiarization of the pump and the rig system and also maintaining pressure at constant rate. The mass flow rate of the desired combination of nozzles at different injection pressure was measured in preparation of the main descaling trials of the constructed wax deposit. The bucket weighing method was utilised and some sequence of experimental procedures were followed to properly measure mass flow rate of different combinations of nozzles at different injection pressures as detailed in [39].

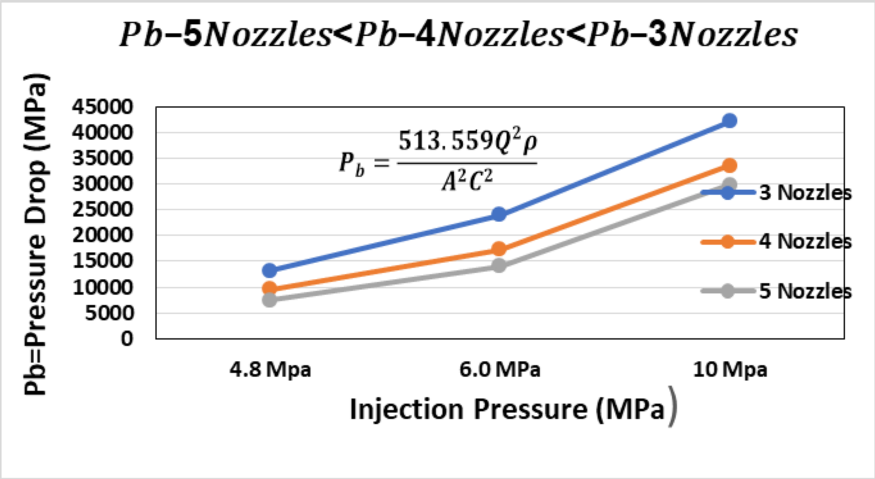


Figure3. 3: Bucket weighing analysis results [39].

3.3. Descaling Performance Evaluation

The descaling result archived from many publications like Experimental Removal of Paraffin Scale Deposit from Petroleum Production Tubing Using Multiple High-Pressure Nozzles and **39-45** established some inter-dependency between some of the descaling parameters used in this study. These are the nozzle configurations, stand-off distance and chamber pressure terms as non-hydro-dynamically connected as they have no affiliation to the mass flow rate of the spray. While numbers of nozzles and injection pressure that are absolutely associated to mass flow rate of the spray are term hydrodynamic connected descaling parameters. Also, despite both deposits being related by their chemical properties, they were found to respond to different jetting mechanisms due to their difference in physical properties like shape and size **[31]** prompting the need for unique descaling conditions that are connected to their physical properties.

Hydro dynamic connected parameters Determination

The most vital set, of all descaling components that determine the direct scale removal force of the jet (kinetic energy and pressure drop across the nozzles) which performance depend on each other are the injection pressure and header configurations (number of nozzles) [32]. The relationship between header configuration and injection pressure is graphically demonstrated in Figure 3.3 and mathematically in equation 1 and 2, as its clear that more injection pressure will be required to produce higher pressure drop with a greater number of nozzles than few nozzles.

3.3.1.1. Optimum Injection Pressure Evaluation

The relationship and high dependency of the amount of scale deposit removed regardless of its type against the utilisation of different injected pressures has clearly been established in [39- 41] and Figure 3.4 to 3.9 were singled out to summarise the finding of the investigations. The effect of injection pressure and its variations on scale removal can be connected by the mathematical expression in Equation 1 and 2 and also Equation 3. Since injection pressure, which is related to the kinetic energy of the spray by direct proportionality with the jet impact or spray velocity, plays the most vital role in removing all the scale types. Where P_d is the dynamic pressure or the injection pressure and V is the fluid velocity.

$$P_t = P_s + P_d \quad (1)$$

$$Pd = Ke = \frac{1}{2}mV^2 \quad (2)$$

$$v = \sqrt{2Pd/m} \quad (3)$$

3.3.1.2. Optimum Number of nozzles Evaluation

The most important of all the descaling parameters and the determinant of the of the jet impact that account for most of the removal is the header configuration. The pressure drop across the nozzles is proportional to the injection, fluid flowrate and inversely to the nozzle's areas (number of nozzles) due to pressure drop effect. Therefore, for same nozzle diameter to generate a large nozzle pressure drop a larger flow rate is required and the fewer the number of nozzles the larger the pressure drop expected [34]. In other words, a higher velocity jet will be yielded from the nozzle that have greater pressure drop [37]. Also, in our case, the scale sample target will be impacted by a high pressure drop (kinetic energy), thereby resulting to sample breakage. Records from the analysis from Section 5.3 of [39] show how much contribution the effect of altering header configuration have made in enhancing the amount of scale removal of the respective scale samples. The effect of pressure drops across multiple nozzles is expressed in Equations 4 and 5 and graphically shown in Figure 3.3, after imputing the generated flowrate results of the bucket weighing experiment into Equation 4.

$$P_b = \frac{513.559 Q^2 p}{A^2 C^2} \quad (4)$$

Were P_b is the pressure drop (MPa), Q is the flowrate (11.3litre/s), p is the density of water (0.98 g/cm^3), C is the nozzle discharge coefficient (0.9) and A is total areas of a nozzle (0.5mm x number of nozzles).

$$P_{b-5nozzles} < P_{b-4nozzles} < P_{b-3nozzles} \quad (5)$$

Hollow soft scale sample

Generally, the removal rates of the hollow shaped paraffin deposit across all the combination of techniques was better than that of the solid shape paraffin deposit. This is as a result of the 30 mm thickness differences of the two samples. In addition to the hollow shaped removal benefited from the fifth jetting mechanism called hoop stress since it is in conformity with the thin wall hoop stress condition [33] as shown in Equations 6 and 7. Where P being internal resultant pressure (chamber pressure+ jet pressure), τ_{hoop} is the hoop stress, r and D are the radius and diameter of the hollow sample and t is its thickness. Also, as already established to be more effectively removed with N-C-N nozzle arrangement due to advantage of absent of centre nozzle diverting the jet strength to the side nozzles that are in good contact with the samples and near jetting position of 25mm due to its better jet impact [39- 44]

$$\frac{Pr}{t} = \tau_{hoops} \qquad (6)$$

$$\frac{D}{t} > 20 \qquad (7)$$

Investigating the impact of altering injection pressures in relations to the amount of scale remove with the NCN nozzle arrangement at 25mm distance in Figure 3.4, 3.5 & 3.6 demonstrated a linear increase in amount of scale remove to increase in injection pressure across all the nozzle configurations. An insignificant increase from 1.8 g to 0.2 g and later 56.3g of mass of paraffin removal was observed after increasing the injection pressure from 4.8 MPa to 6 MPa and subsequently to 10 MPa when descaling with 5nozzles configuration as shown in Figure 3.4. While same figure demonstrated how descaling operations with 4 nozzles at 4.8 MPa initially removes 4.8g of scale deposit that slightly increase by 1.8g and further skyrocketed by almost 69g after increasing the injection pressure by 1.2 MPa and subsequently by 5.2 MPa. Better result of removal value of 42.8g was initially achieved with 4.8 MPa injection pressure of 3 nozzle configuration that doubled by 50.9g and subsequently almost a fourfold increase (209g) after trothing to 6.0 MPa and later 10MPa respectively. Reducing the numbers of nozzle to 3 nozzles at ambient condition show greater impact than 4 and 5 nozzle header configurations due to multiple nozzle pressure drop effect [37]. A very small difference of rate of scale removal of 3g from 1.8g was recorded when the nozzle configuration was reduced from five to four nozzles. Contrary to the almost 17 times increase of 38g to be precise, when further reducing the numbers of nozzle to three nozzles from four nozzles at same 4.8 MPa injection pressure as shown in Figure 3.4. Also further reducing the number of nozzles from 5 to 4 when operating at 6.0 MPa doubled the removal from same 1.8g by 3.6g and subsequently by 84g after reducing to 3 nozzles which was able to pictorially break the sample. The analysis of the impact of number of nozzles at 10 MPa injection pressure demonstrated a good result that qualitatively broke through all the descaled samples across the 5, 4 & 3 nozzles configurations. The value of 58.1g of scale removed with 5 nozzles at 10MPa was slightly increased by 12.1g and consequently by 184g after reducing the header configuration to 4nozzles and later 3nozzles respectively due to pressure drop effect on the nozzles manifold.

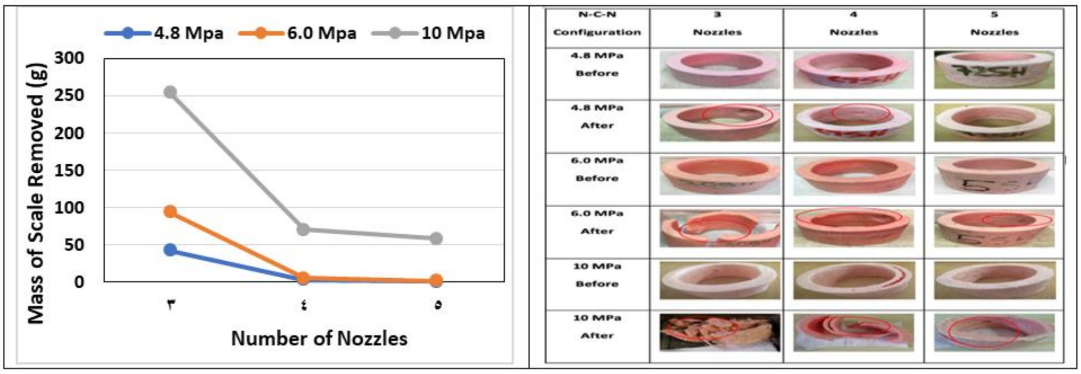


Figure 3. 4: Descaling results of hollow shaped paraffin scale deposits in ambient chamber condition.

The outcome of investigating the effect of altering injection pressures and number of nozzles when removing hollow shape scale deposit in a compressed chamber air condition at 25mm stand-off distance and N-C-N nozzle configuration as presented in **Figure 3.5**. Proves to share similar but more impressive descaling trend with ambient removal operations due to the introduced 0.2MPa compression that enhance both erosion, cyclin stress and aberrational jetting mechanism on the samples. This can be qualitatively proven where even the 4.8MPa pressure removal result across 5, 4 & 3 nozzles at ambient pressure was increases by 2.3g, 3.5g & 13g respectively. The five nozzles at at low pressure of 4.8 MPa initially removed 4.1g of scale that was slightly improved by 1.5g and subsequently 58g with corresponding increase of injection pressure to 6.0 MPa and later 10 MPa. This was almost fifty times increased attributed to the wide pressure variation between 10 MPa injection pressure and that of 4.8 & 6.0 MPa. The 4nozzle configuration started by removing 6g at 4.8 MPa injection pressures that was a bite raised by 5.3g after increasing to 6.0 MPa and increasing the injection pressure to 10 MPa resulted to a massive growth of descaling rate by 131g. Whereas, the 3nozzle configuration was able to highly increase the initial removal at low pressure of 4.8 MPa to 47g that was tripled by 161.1g and more by 184g due to the increase of injection pressure to 6.0 MPa and subsequently 10 MPa. Analysis of the impact of altering header configurations for corresponding injection pressure shows that pumping water at low pressure of 4.8 MPa with five nozzles removed 4.1g of scale that insignificantly increase by 1.8g and substantially by 44.7g after reducing the numbers of nozzles to 4 and later 3 configurations. Picture wise, **Figure 3.4** displayed some holes across all the 4.8 and 6.0MPa descaled samples at 5 & 4 nozzle configurations experiments with the exception of the 3 nozzles that broke the sample with 6.0MPa injection. While increasing the injection pressure to 6.0MPa with 5nozzles configuration initially removed 5.3g of scale that was improved by 7.1g and substantially more by 197g after adjusting the header configuration to 4nozzles and later 3nozzles. However, altering the nozzles configurations at high pressure of 10 MPa yielded the highest scale removal result with the highest variation observed between three and four nozzles. Pumping at high pressure of 10 MPa with five nozzles resulted to the substantial removal of 56g of scale that was increased by 78g after reducing to four nozzles. This was further highly increased by 155g after subsequently reducing to three nozzles. Figure 3.5 pictorially marked all then nozzle configuration trial with broken descaled samples.

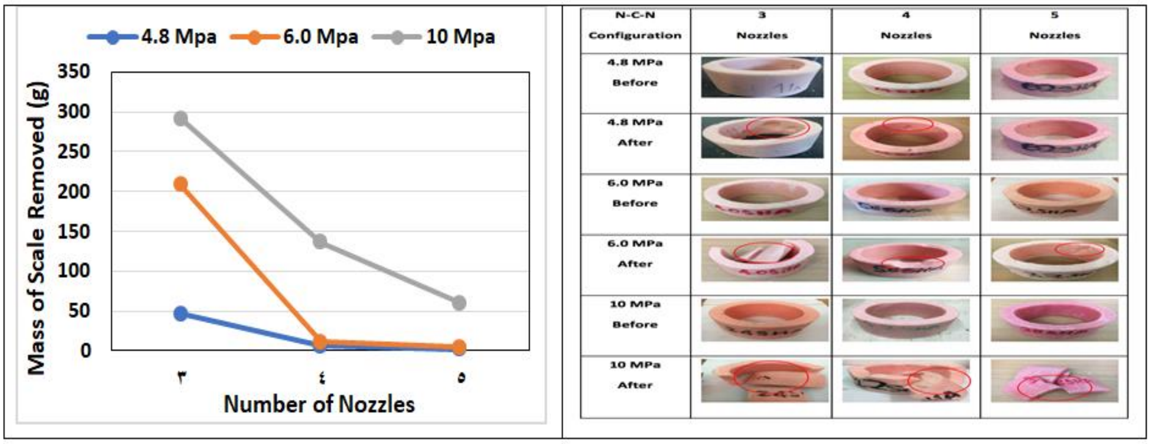


Figure 3. 5: Descaling results of hollow shaped paraffin scale deposits in compressed chamber condition.

The results of hollow shape soft scale descaled in a suctioned chamber air conditions in **Figure 3.6** proves to have attained better scale removal than both ambient and compressed trials due to the introduced suction air into the chamber using the vacuum pump enhances both erosion, cyclin stress, sample particle abrasion mechanism and hoop stress onto the samples. The five-nozzle configuration vacuumed descaling experiment was able remove 5.2g of paraffin at low injection pressure that improves by 7.6g and much more by 90g at medium and high injection pressure respectively. Reducing the number of nozzles to 4 nozzles at lower pressure (4.8 MPa) improve the removal to 10g that was later improved by 9.7g and by fifteen time (115.5g) due to subsequent increase of the injection pressures to 6.0 and 10 MPa respectively. Further reduction of the header configuration to 3 nozzles at 4.8 MPa injection produces the highest initial paraffin removal of 80g that was later improved by 109g and doubled by (163.3g) after rising the injection pressure to 6.0 and later 10 MPa respectively. Also, the best set of quantitative and qualitative result of hollow paraffin removal regarding the impact of altering header configurations for corresponding injection pressure was attained in the vacuumed descaling trials that is presented in the **Figure 3.6** below. Starting by injecting water at low pressure of 4.8 MPa with five nozzles initially removed 5.2g of paraffin that insignificantly increase by 2.5g and shoot up by 83.4g after altering the header configuration to 4 and subsequently 3 nozzles configurations. **Figure 3.6** exhibited holes being drilled across all the descaled samples at 5 and 4 nozzle configurations with low and medium injection pressure and subsequent scale breakage for the high injection pressure trials respectively. Subsequent increase of the injection pressure to 6.0 MPa with 5 nozzles configuration increase the initial paraffin removal to 7.6g that was boosted by 11.6g and skyrocketed by 203.3g as a result of altering the header configuration to 4 nozzles and subsequently 3 nozzles. The further increment of injection pressure to 10 MPa with five nozzles configuration that generated a high removal of 61.2g of paraffin and later substantially improved by 73g and much more by 225g was the consequences of varying the header configuration to 4 & 3 nozzles respectively. **Figure 3.6** showcase the best and breakthrough qualitative results of removing paraffin that breaks all the samples across all the injection pressure with 3 nozzles configurations.

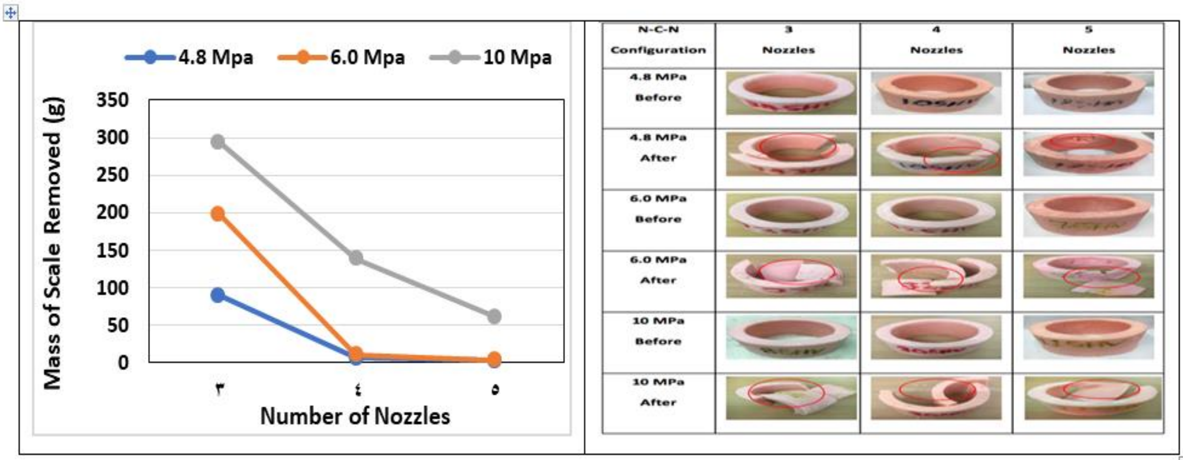


Figure 3. 6 : Descaling results of hollow shaped paraffin scale deposits in vacuumed chamber Condition.

Solid soft scale sample

The solid soft scale removal experiment results shown in **Figure 3.7, 3.8 & 3.9** were found to share similar descaling trend with the hollow removal even though less impressive due to the 30mm thickness difference but more effectively removed by the CN followed by the CNO nozzles arrangement due to the introduce centre nozzle having good contact the the scale surface that at same time aid particle abrasion mechanism [39-44].

A mass of 1.4g was initially removed with 5 nozzles at 4.8 MPa injection and increases by 2g & 24.7g after increasing the pressure to 6.0 & 10 MPa respectively. While the 4nozzle operation removed 2.8g of solid scale deposit at 4.8 MPa that slightly increases by 1g and significantly increase by 48.1g after throttling to 10 MPa. More significant removal can be sighted in **Figure 3.7** where the 3nozzle operation originally removes 4.7g of scale at 4.8 MPa injection, that slightly increase by 2.1g and later by many folds of 97g as a result of subsequent increase of the injection pressure to 6.0 MPa and 10 MPa respectively. Operating 5nozzles at 4.8 MPa initially remove 1.4g of scale that increases by 1.5g and 5.4g after reducing the number of nozzles to 4 and later 3nozzle with no noticeable qualitative impact in **Figure 3.7**. Injecting at 6.0 MPa with 5nozzles was able to remove 1.8g of scale that was rise by 1.9 with 4nozzles and better off by 4.5g after reducing to 3nozzles were some holes were drilled across Figure **3.7**. The utilization of 5nozzles at of 10 MPa was able to substantially remove 27g that increased by 25g and later almost 53g after reducing the nozzles numbers to 4 and later 3nozzles that was able to break all the samples in **Figure 3.7**.

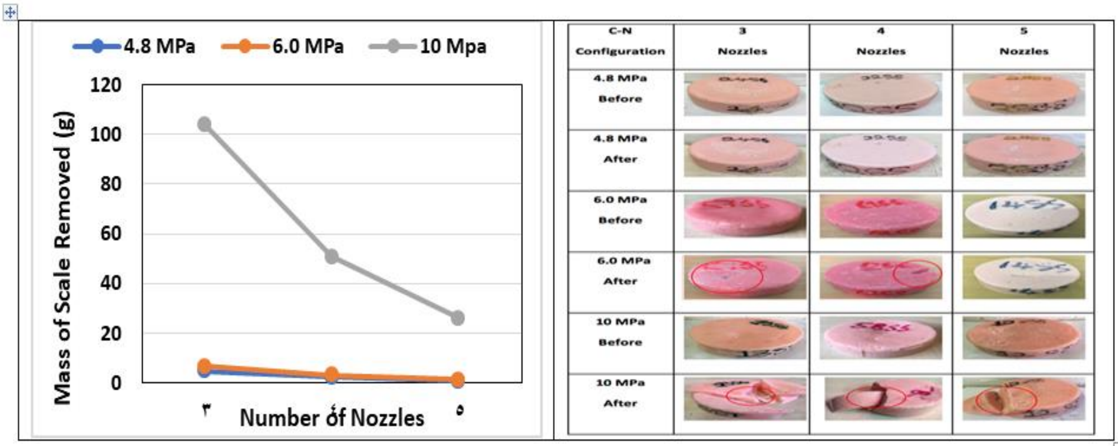


Figure 3. 7: Descaling results of solid shaped paraffin scale deposits in ambient chamber condition.

Descaling soft solid scale in compressed condition lead to the breakthrough of breaking solid scale samples at even lower injection pressures. Utilising 4.8 MPa with 5nozzles removed 2.5g that increase to 0.7g and much better by 47.7g, while with 4nozzles removed3.9g and increase by 6 that skyrocketed by 124g due to subsequent adjustment of injection pressure to 6.0 and later 10 MPa. Varying the nozzle configuration to 3nozzle at 4.8 MPa increase the removal to 12.8g that was increased by 7g and highly improved by 212g as a result of trothing up the injection pressure by 1.2 MPa and subsequently 5.2 MPa. Varying the header configurations from 5 to 4 & 3 nozzles configuration at 4.8 MPa removed 2.5g of scale that consequently increases by 1.8g and later 9.6g respectively with holes all crossed the entire nozzles configuration trials in **Figure. 3.8**. The 6.0 MPa injection operation visually cracked the 5nozzles configuration sample and broke both the sample of the 4 & 3 nozzles configuration that started by removing 2.7g that increase to 8.1g and later 11.4g after adjusting the header nozzles from 5 to 4 and later 3nozzles configuration. High scale removal of 50g that increase by 73g and further by 97g was achieved after reducing the number of nozzles of the 10 MPa 5nozzles operation to 4 and later 3nozlles that visually break all the samples in the entire campaign.

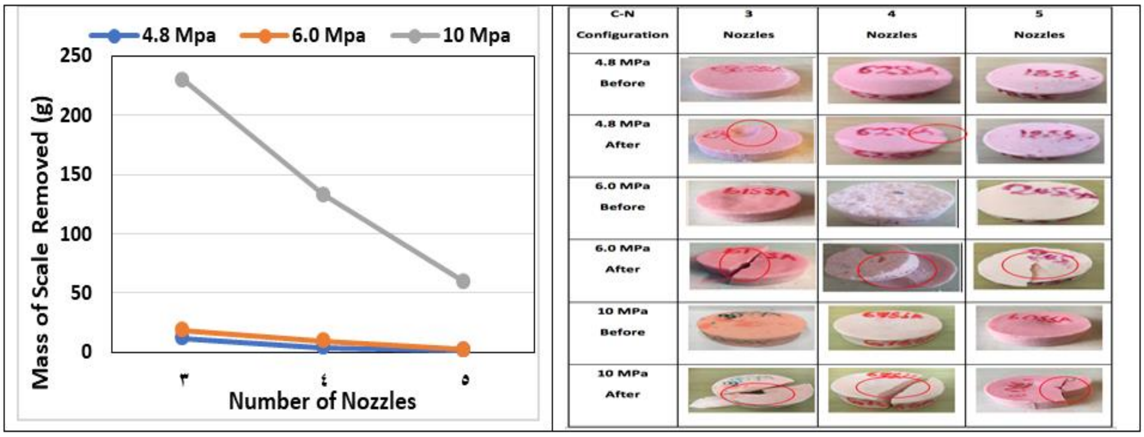


Figure 3. 8: Descaling results of soli shaped paraffin scale deposits in compressed chamber condition.

The descaling results attained from the removal of solid scale samples in vacuumed conditions with all the nozzle configurations and injection pressure with NC-configurations descaled more paraffin deposit than the ambient but slightly less than compressed chamber condition experiments. The investigatory results from 5 nozzle configuration vacuumed descaling experiment at low pressure initially removes 2.1g of paraffin that improves by 3.8g and much more by 58.g at both 6.0 and 10 MPa injection pressure respectively. Adjusting the header configuration to four-nozzles at lower pressure (4.8 MPa) improve the initial removal amount to 3.8g that was boosted by 7g and better off by 123g as a result of the subsequently increasing the injection pressures to 6.0 and 10 MPa respectively. Further adjusting the header configuration to 3 nozzles at low pressure of 4.8 MPa removed substantial amount of paraffin (12g) that was improved by 7.8g and skyrocketed by 211g due to the effect of rising the injection pressure to 6.0 and subsequently 10 MPa respectively. In terms of investigating the effect of nozzle configuration when removing solid shape paraffin samples, vacuumed descaling result was a breakthrough of the campaign with impressive qualitative and quantitative result presented in the **Figure 3.9**. The experimental results of utilising low pumping pressure of 4.8 MPa with five nozzles started by removing 2.1g of paraffin that improved by 1.7 and more significantly by 12g due to the subsequent alteration of the header configurations to 4 and 3 nozzles configurations respectively. Throttling the injection pressure to 6.0MPa with 5 nozzles configuration rised the initial paraffin removal amounts to 2.7g that was furthered by 8.3g and by also 11g because of the header configuration alteration to 4 nozzles and 3 nozzles respectively. Improved qualitative descaled result that drilled holes almost across all the nozzles configurations of the low pressure operations and complete scale breakage across all nozzles configuration of the medium and high injection pressure is displayed in **Figure 3.9**. Finally, trothing the injection pressure further to 10 MPa with five nozzles configuration produced an impressive paraffin removal result of 51g that doubled by 73g and boosted further by 92g from the consequences of header configuration alteration to 4 and subsequently 3 nozzles. **Figure 3.9** displayed a breakthrough qualitative results of removing solid shape paraffin that breaks all the samples across all header and nozzle configurations.

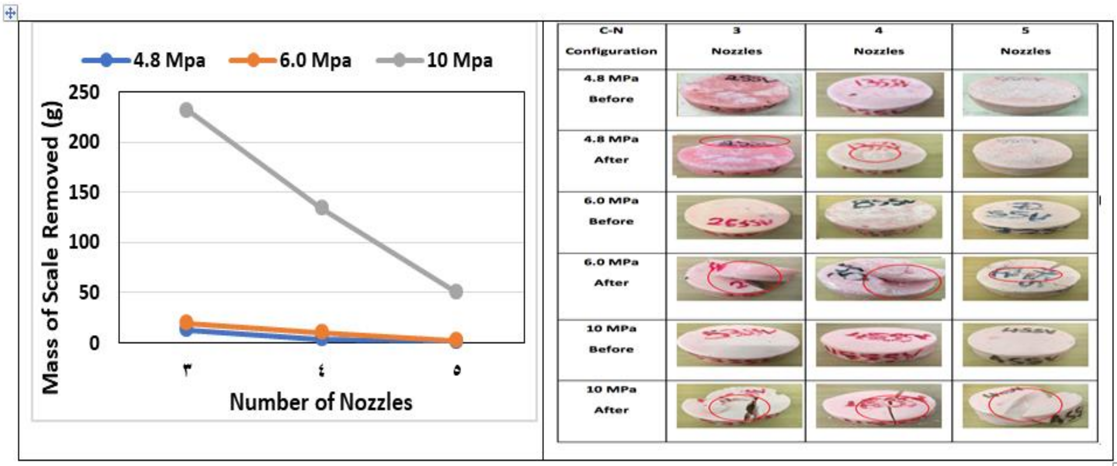


Figure 3. 9: Descaling results of solid shaped paraffin scale deposits in vacuumed chamber condition.

3.3.2. Non-hydrodynamics Connected Parameters Determination

The selection of the best non-hydrodynamics connected parameters like stand-off distance and nozzles configurations which have no direct effect to the pumping requirement, mass flow rate but interact with each other during the operations seems to play a vital role in enhancing the removal of all the types of scale deposits.

3.3.2.1. Optimum Standoff Distance Evaluation

The case of adjusting downstream distance during the experiment demonstrated a trend that reduces the amount of scale removed with an increase in stand-off distance irrespective of shape or size of the scale deposit. We're spraying from 25mm stand-off distance produced the most effective removal result that subsequently reduced after moving the sample 50mm away from the atomizers and completely inefficient after further moving the sample 75mm from the nozzles header due to reduction of jet impact on the scale surface [2]. This observation is consistent with findings from similar studies on the HP water jets oilfield descaling researches [1, 2, 39, 40,41,42,43,44 & 45]. Even though, on some occasions far jetting position of 50mm distance were able to efficiently perform or even break the samples as a result of good nozzle arrangement selection.

3.3.2.2. Optimum nozzle arrangement determination

Nozzle arrangement selection depends on the shape of the deposit in question for more efficient removal as a result of the good jet impact and jet profile. Since complete target surface coverage has been categorized as the most essential requirement for achieving effective descaling results [11&15]. The result from the utilization of the non-centre nozzle arrangement or (NCN) demonstrated suitability in removing early-stage growth of paraffin deposit in production tubing [42]. This can be attributed to the absence of centre nozzle diverting the jet impact to the side nozzles that are in good contact with the paraffin scale surface. The introduction of the centre nozzle in centre nozzle arrangement (CN), show more efficiency in removing complete paraffin scale tubing blockage because of the introduced centre nozzles having a higher kinetic impact than the side nozzle and spray directly on the surface of the scale deposit. Furthermore, centre nozzle overlap arrangement or (CNO) is also found more preferable in complete tubing blockage cleaning, although less effective compared to the CN arrangement due to complete spray overlap jet profile tubing constraint that ends up spraying the tube instead of the deposit [39]. Also coupled with the highest droplet velocity concentrating toward the centre of spray overlap region [27] that was distrusted. However, the introduction of the centre nozzle in both CN and CNO arrangement for the removal of early deposition stage in production tubing was found inefficient, and not suitable throughout the experiment.

3.3.2.3 Optimum Chamber Pressure Evaluation

The effects of altering chamber air pressure (chamber water-air ratio) affect both the jetting mechanism and the resultant impact of the jets, which are constant or not altered at ambient chamber air concentration [41]. While the kinetic energy of the jet was suppressed by the introduction of the 0.2MPa compressed air that aided both cyclic stress mechanisms and particle abrasion of the samples [1]. Whereas the kinetic energy of the jets was increase as a result of suctioning the chamber to $-8x10^{-3}$ MPa and further enhanced the hoop stress mechanism on the samples [39] as shown in Equation 8. The soft hollow shaped removal benefited from the hoop stress mechanism because it aligned to the hoop stress thin-walled condition as expressed in Equation 6 & 7, making it slightly more impressive under vacuum pressure ($-8x10^{-3}$ MPa) than compressed air pressure (0.2MPa) and appreciably better than ambient pressure. While the solid shaped deposit benefited more from the introduction of the compressed air into the chamber as a result of cyclic stress due to additional fatigue stress from the compression. Suctioning the chamber by -0.008MPa increased the kinetic energy of the jet and enhance the hoops stress mechanisms on the samples as in Equation 8.

$$\tau_{\mathrm{hoopVac}} > \tau_{\mathrm{hoopAmb}} > \tau_{\mathrm{hoopCom}} \qquad (8)$$

Generally, irrespective of the combination of scale removal parameters, the result achieved from removing hollow shaped paraffin was better than that of the solid shaped paraffin deposit. This can be attributed to the 30mm thickness differences of the two samples. In addition to the hollow shaped removal benefited from the fifth jetting mechanism called hoop stress, since conforms with the thin wall hoop stress condition as earlier on expressed in Equation 6 and 7 and also equation 9 of [45].

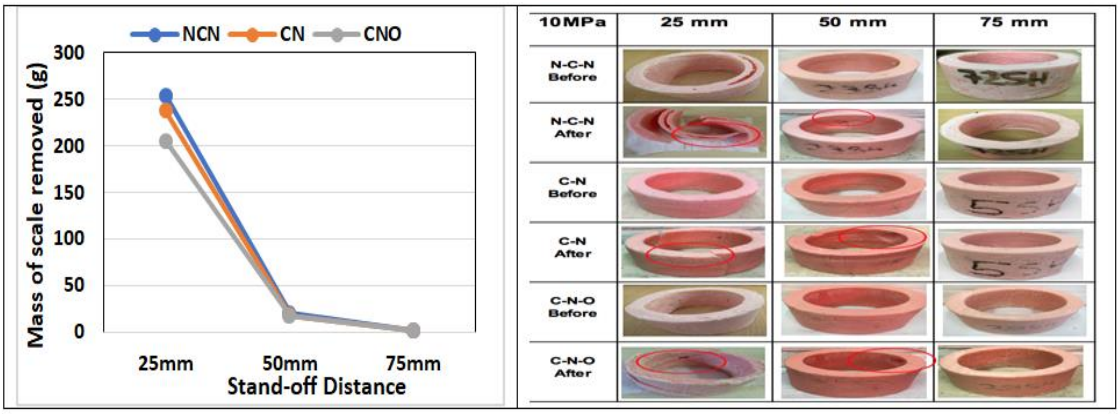


Figure 3. 10 : Descaling results of hollow shaped paraffin scale deposits in ambient chamber condition.

Although, in reference to Figure 3.10, the impact of varying chamber pressure while removing both scale deposit irrespective of the other utilized descaling parameters is noticeable and highly aided all the respective jetting mechanisms [39]. The ambient chamber pressure scale removal results are not as effective as those from the compressed or vacuumed condition experiment due to the jet impact being been unaffected and only able to utilize the kinetic erosional jetting mechanism. Even though, the hollow shaped paraffin removal at ambient chamber pressure reasonably benefitted from the hoop stress jetting mechanism as a result of concurring to the thing walled hoop stress condition as shown in Equation 6 and 7. Descaling results from the adjustment of the downstream distance between the atomizers head and the descaling samples yielded the most effective results at 25mm positioning, poor and very poor result from the 50mm and 75mm distance respectively due to poor jet to scale target impact (jet-profile) [28]. A very poor average removal rate of 1.1g across the three nozzles arrangement was significantly quantitatively improved by almost 20g after reducing the standoff distance from 75mm to 50mm distance and qualitatively to drilling holes across the samples. Impressively, an average paraffin removal increase by almost 212g and sample breakage across all the respective nozzle arrangements was recorded quantitative wise as shown in Figure 3.10 as a result of moving the header to 25mm jetting position. Nozzle arrangement is probably the most effective descaling parameter during the experiment with a noticeable impact. Despite, found governed by the shape of scale deposit in question, it's found vital in selecting other descaling parameters for effective results. Although its impact is more noticeable at lower stand-off jetting position (25mm) than the rest, where all the descale sample were qualitatively broken and a quantitative total removal difference of 95g and 198g was recorded between the NCN and other nozzles arrangement from the three respective jetting positions. The triangle nozzle arrangement (NCN) was more effective because the absence of the centre nozzle diverted the jet strength to the side nozzles that are in good contact with the scale surface. While the introduction of centre nozzles in the diagonal CN arrangement ineffectively spray through the hollowness of the sample, so also the spray overlap impact of the right-angle CNO arrangement end up distorting the jet profile and spraying the chamber tube instead of the deposits.

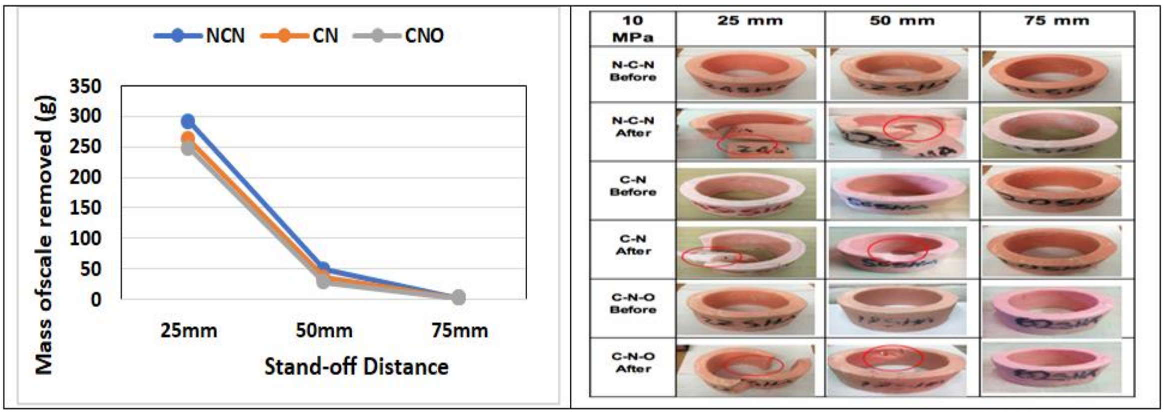


Figure 3. 11: Descaling results of hollow shaped paraffin scale deposits in compressed chamber condition**.**

The introduction of 0.2MPa compressed air into the system increased the amount of scale removed due to the extra fatigue induced on the deposit in addition to enhancing both erosions, cyclin stress and sample particle abrasion jetting mechanism despite suppressing the kinetic impact of the sprays. An average paraffin removal increase of almost 38 g was recorded at the 25mm jetting position compared to the ambient chamber condition result in **Figure 3.11** with remarkable qualitative improvement. While an average qualitative removal difference of 10 g was achieved at a 50mm distance with scale breakage at the NCN arrangement. Although the result of ambient and compressed chamber results was not impressive at 75mm distance with removal difference of less than 1 g. The effect of altering jetting position in compressed descaling experiment plays a vital role in enhancing scale removal and followed a similar removal trend with that of ambient chamber experiment, although with improvement in removal rate and more effective at 25mm distance. An increase in average removal of almost 28g and 263g was observed as a result of reducing the jetting position from 75mm to 50mm and later 25mm distance respectively as shown in **Figure 3.11**. Similar to the ambient chamber experiment where the nozzle arrangement responds better at 25mm distance positions and removes more deposits with triangle NCN arrangement due to the absence of the centre nozzle diverting the jet strength to the side nozzles that are in good contact with deposits. A total removal difference of 55g and 66g was recorded between triangle NCN and other nozzle arrangements at all the respective stand-off distance and also an average removal difference of 67g between the NCN nozzle arrangement of compressed and that of the ambient chamber pressure results respectively.

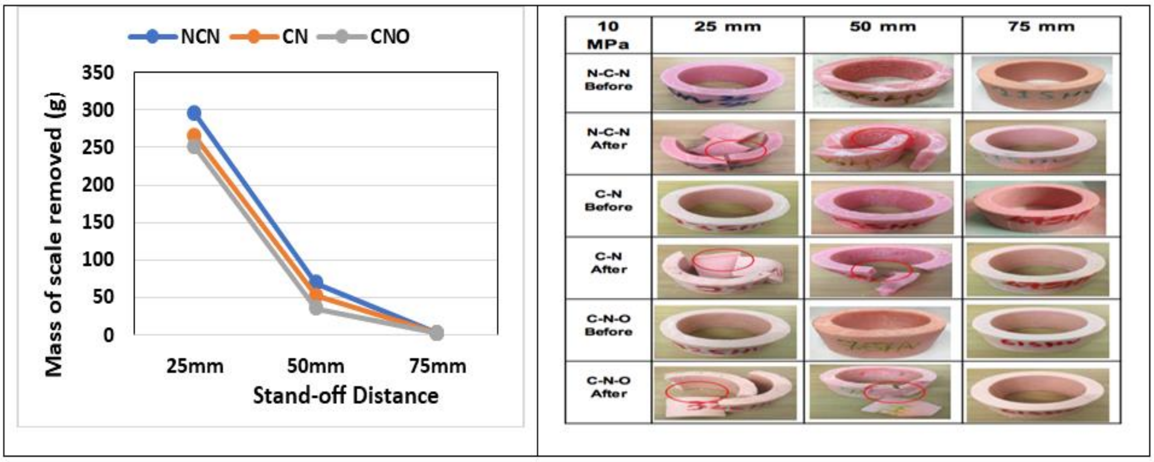


Figure 3. 12 : Descaling results of hollow shaped paraffin scale deposits in vacuumed chamber condition.

The descaling option of suction the chamber by -0.08Pa while removing hollow shaped sample provides the most impressive descaling results compared to the other two-chamber conditions by enhancing both erosional, cyclin stress, cavitation and hoop stress jetting mechanisms. An average significant paraffin scale removal difference of 10g and 40g can be graphically sighted between the 25mm distance position of vacuumed and other respective chamber pressure and also 15g & 32g at 50mm position that qualitatively broke all the samples as shown in **Figure 3.12**. Likewise, the effect of altering jetting position in vacuumed chamber pressure yielded the best results in removing hollow shaped scale deposits by significantly qualitatively breaking all the scale deposit at a higher standoff position of 50mm with all the respective nozzles arrangement as shown in **Figure 3.12**. A Significant increase in average removal of 50g and 268g of paraffin deposit was sustained after subsequent reduction in jetting distance from 75mm to 50 and further 25mm distance. The results from the investigation of the effect of nozzle configuration when removing hollow shaped scale deposit in a vacuumed chamber air concentration at different stand-off distance as presented in **Figure 3.12**. The NCN triangle nozzle arrangement is still the tip to be most effective among others. As a total removal value of 217g that was initial achieved with right-angle CNO arrangement crossed the three distance was increased by almost 100g after altering the header configuration to the diagonal CN arrangement by introducing centre nozzle. Furthermore, increase the removal difference by 198g after blocking the centre nozzle to achieve the triangle arrangement of the NCN configuration. A very impressive visual result can be sighted in **Figure 3.12** where all the descaling sample utilized at 25mm and 50mm distance irrespective of the nozzles arrangement were broken, if not of the 75mm operations that remain impressive.

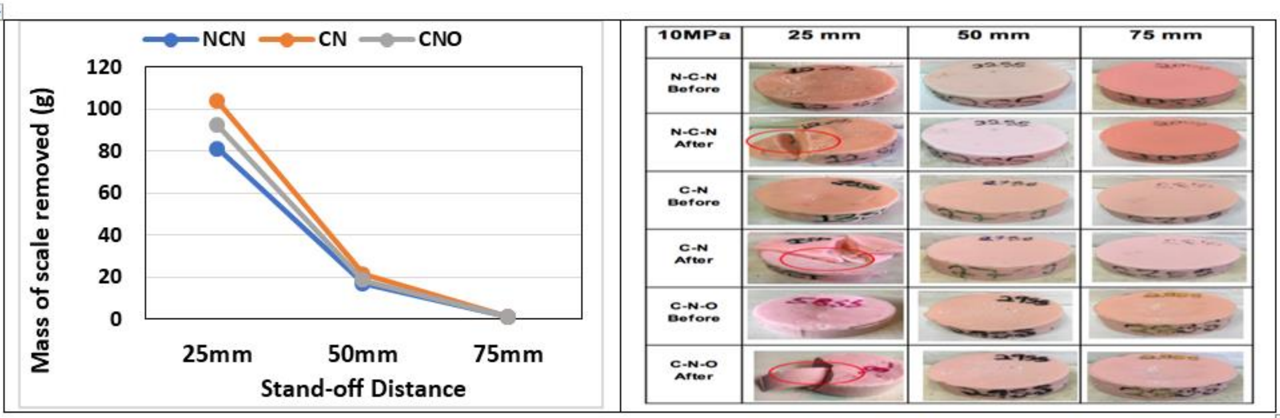


Figure 3. 13: Descaling results of solid shaped paraffin scale deposits in ambient chamber condition.

Figure 3.13, 3.14 and **Figure 3.15** demonstrate both quantitative and qualitative results generated from the descaling investigation of solid shaped scale samples at respective chamber pressure, standoff distance and nozzles arrangement. The set of results exhibited a similar descaling trend to that of the hollow soft scale sample removal even though with less impact due to the difference in thickness of the samples. The three-minute ambient solid shaped scale descaling results were averagely almost 140g less effective in paraffin removal compared to hollow scale descaling results at respective nozzles arrangements from the 25mm stand-off distance due to the difference in thickness and shapes of the samples. Similar to the entire hollow experiments were 75mm distance descaling result was very poor with some significant increase and a very effective result as a result of reducing the jetting position to 50mm and subsequently 25mm. The 75mm distance ambient solid descaling initially removes an averagely of 1.1g of paraffin across the respective nozzle configuration that averagely increases by 18g after altering standoff distance by 25mm. While further reducing the jetting position by 25mm skyrocketed the average paraffin removal rate by 90g. Also, pictorially, **Figure 3.13** showcase a poor uniform erosion across the board for the 75mm and 50mm distance respectively and scale breakage for the entire respective nozzles' arrangement of 25mm jetting position. Contrary to the paraffin removal results from the hollow shape sample experiment where NCN arrangement lead to CN and CNO removal in terms of removal performance, since the selection of nozzle arrangement is governed by the shape of the descaling sample. The solid shape solid removal experiment found the CN (diagonal) arrangement more suitable due to the introduced centre nozzle with high jet impact been in direct contact with scale deposit in addition to particle abrasion and lifting advantage to others. While the NCN triangle arrangement ends up spraying the tube and so also the overlapping impact of the CNO right-angle arrangement. **Figure 3.13** showcase a quantitative paraffin removal difference of 12g & 23g and also 2g & 1g between CN, CNO and NCN nozzle arrangement at 25mm and 50mm distance respectively.

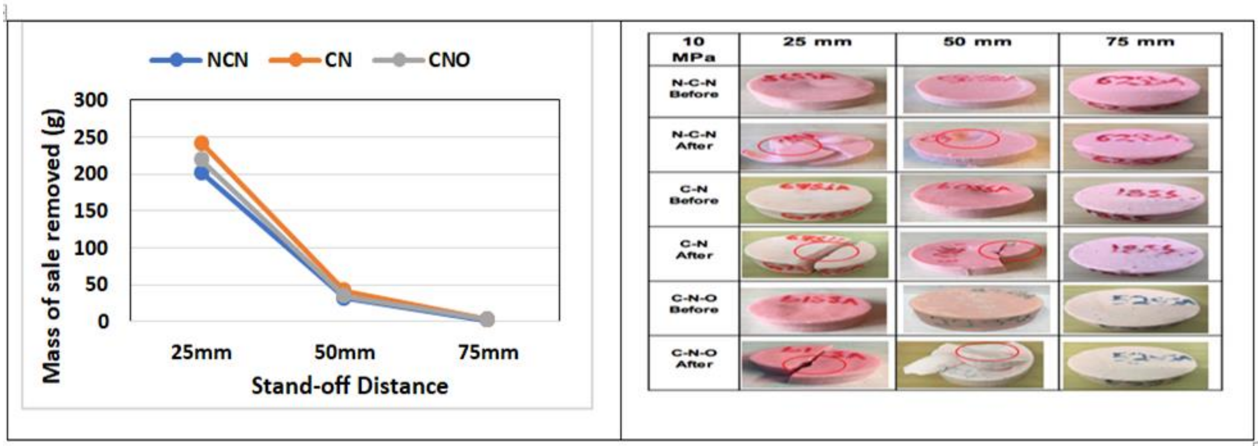


Figure 3. 14: Descaling results of soli shaped paraffin scale deposits in compressed chamber condition.

As earlier mentioned, that the introduction of 0.2MPa compressed air into the chamber aided the cyclin stress removal mechanism of the solid soft shape deposit as a result of the additional fatigue induced on the samples from the compression **[24].** The compressed air descaling option produced a better result than the remaining chamber pressure experiment in removing solid shaped samples against that of hollow shaped removal that works better in vacuumed chamber condition. Despite the entire solid shaped removal result lagging the hollow shaped result, an impressive result can be quantitatively and qualitatively sighted in **Figure 3.14**, where an average paraffin removal difference of 128g & 6g was observed between the compressed, vacuumed and ambient operations at 25mm distance. Similarly, at 50mm distance, a removal difference of 5g & 17g was also recorded between the compressed and vacuumed operation and also ambient respectively with approximately 1g difference across the entire chamber pressures result of the 75mm jetting position. The effect of standoff distance in removing solid scale sample was found to be similar to that of a hollow sample, although with improvement at 50mm jetting position were both the diagonal and right-angle nozzle configuration were able to break the samples as shown in **Figure 3.14**. The 75mm jetting position, as usual, produce a very poor average descaling result (2.4g) that is not responding to other descaling parameters which increases by many folds (34g) as a result of reducing the jetting position to 50mm distance. While further reducing the allowance between the deposit and the nozzles header by 25mm skyrocketed the average paraffin removal amount by 218g and breaks all the samples across at the respective nozzles arrangement as captured in **Figure 3.14**. The compressed chamber solid scale removal experiment conforms to the CN followed by CNO and NCN nozzle arrangements ranking order where CN averagely removes almost 10g more than the CNO arrangement and almost 17g better than the NCN arrangements due to the already established factors.

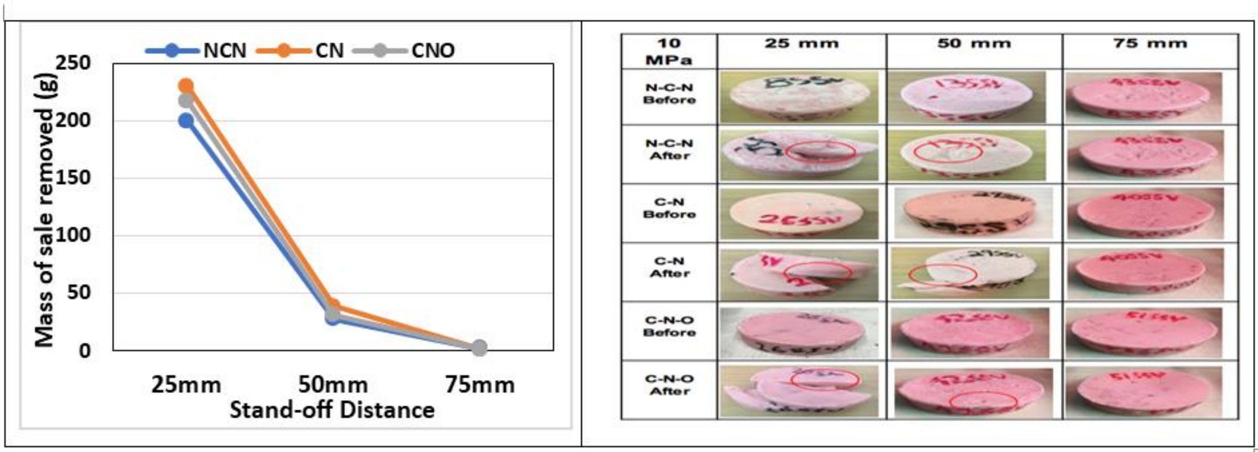


Figure 3. 15: Descaling results of solid shaped paraffin scale deposits in vacuumed chamber condition.

The descaling option of introducing (-0.08MPa) suctioned air into the chamber while utilising other descaling parameter was the vital reason for the additional scale removal compared to ambient operations, although less effective than compressed experimental results. Similarly exhibiting a descaling trend that increases with the decrease of stand-off distance and better off with centre nozzle arrangements (CN) due to the presence of the centre nozzle that is in good contact with the face of the solid shape sample. Despite the remarkable performance by the vacuumed descaling option in removing solid shape paraffin scale, it was found slightly lagging behind the compressed chamber option and far better than the ambient chamber alternative. The vacuumed chamber remarkable performance as quantitatively and qualitatively demonstrated in **Figure 3.15** proves to be averagely 124g better than ambient condition and just 6g less than the compressed chamber option across the respective nozzle arrangements of 25mm distance operations. The case of stand-off distance alteration impact when utilizing the vacuumed chamber option to remove solid shape paraffin was not different to that of the other chamber pressure conditions where the closer the spray distance the better the impact. Even with the introduced suction air, the 75mm distance results remain inconsequential with an average removal of 1.7g across all the respective nozzle arrangement with almost 31g increase and material breakage in CN arrangement as shown in **Figure 3.15** after reducing the distance to 50mm. While further reducing the jetting distance by 25mm significantly raise the average removal rate by almost 214g. Similar to the other chamber pressure conditions, the vacuumed chamber pressure results were the CN diagonal arrangement is 13g better than the CNO and almost 30g than the NCN arrangements at 25mm distance as shown in **Figure 3.15**. While at 50mm distance, a significant average removal difference of 7g and 11g were observed between CN and CNO & CN and also the entire results of the 75mm distance poorly (0.1g) responds to the nozzle arrangement alteration parameter as shown in **Figure 3.15**.

Finally, **Table 4.1** summarized the descaling requirement of cleaning both partially paraffin blocked tubing and complete blocked tubing when utilizing multiple nozzle header of 5, 4 or 3 number nozzles at NCN, CN or CNO nozzles arrangements. While also simultaneously spraying solid free ambient temperature water at 4.8, 6.0 or 10MPa injection pressure in ambient, compressed or vacuumed chamber pressure conditions.

Table 4.1: Multiple High-Pressure Circular Nozzle Descaling Operations Guide.

DESCALING PARAMETERS SELECTION GUIDE FOR PARAFFIN DEPOSIT																	
Scale Deposit Type	**Scale Deposit**	**Header Configuration**			**Injection Pressures (MPa)**			**Stand-off distance (mm)**			**Nozzle Configurations**			**Chamber Pressure (MPa)**			**Efficiency (%)**
	Shape	**5**	**4**	**3**	**4.8**	**6.0**	**10**	**25**	**50**	**75**	**NCN**	**CN**	**CNO**	**-0.008**	**0.101**	**0.2**	
Paraffin (CnH2n +2)	**Hollow**			**√**			**√**	**√**			**√**			**√**			**25**
	Solid			**√**			**√**	**√**				**√**				**√**	**19**

4. Conclusion

- Considering the distinct chemical and physical properties of each scale deposit, will consequently respond to different erosional mechanisms and require unique optimised descaling conditions for its effective descaling.
- Therefore, the selection of the best descaling requirement for each deposit depends on the shape, size, hardness and location of the deposit in question.
- Consequently, a high level of interaction and dependency between all the descaling parameters and the amount of scale removed, especially within the hydro dynamic connected and non-hydro dynamic connected parameters respectively exist.
- The amount of scale removed irrespective of type of deposit in related to the hydrodynamic parameter's increases with increase with injection pressure (kinetic energy) and decrease with increase in number of nozzles (header configuration) due to multiple nozzle pressure drops effect.
- While the amount of scale removed for all the respective deposits in connection with the non-hydrodynamic parameters decreases with increase in jetting position and the poor downhole jet performance can be corrected with the right choice of nozzle configurations
- So also, the selection of nozzle configuration (header arrangement) is govern by the size and shape of the sample, as NCN configuration was able to remove 7% & 13% more than CN and CNO configuration when descaling hollow shape scale at the best of other parameters in ambient condition. While CN configuration removed 6% & 4% more deposit of solid than the CNO and NCN nozzles configurations respectively.
- Fifth descaling mechanism (hoop stress) effective in removing early growth stage scale deposit (hollow shape) was discovered and was found to be more active in suction chamber condition together with cavitation mechanism. Even, though the compressive chamber condition was more effective in removing complete tubing blocked deposits (solid) than hollow shape deposit that does not fulfil the hoop stress tin wall condition through erosion, cyclin stress and particle abrasion mechanism
- The introduction of 0.2 MP compressed air into the chamber with the best parameters approximately

increase the removal of hollow by 23% and the solid shape by 27% through enhancing cycling stress and particle abrasion jetting mechanism.

- While suctioning the chamber by -0.008MPa when utilising the best parameters increases the average ambient removal of hollow shape deposit by 26% and the solid shaped by 18% through enhancing kinetic energy, hoops stress, particle abrasion and cavitation jetting mechanism.
- The hollow shape paraffin deposit was the only deposit that was effectively removed in ambient chamber condition due to hope stress effect and was only lagging by 38g and 40g behind the compressed and vacuum chamber condition removal respectively.

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