American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

Investigating the Impact of Non-Hydrodynamically Connected Descaling Parameters in the Removal of Different Stages of Paraffin Deposits Using Multiple Nozzles in Petroleum Production Tubing

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Abstract

Despite the continued research efforts in understanding the erosional behaviors of multiple flat fan nozzles in the removal of different types of scale deposits from petroleum production tubing. The non-hydrodynamically connected descaling parameters such as stand-off distance, nozzle arrangement and chamber pressure have not been duly considered up to date. This research utilizes 3-flat fan high-pressure nozzles at a high injection pressure of 10 MPa to remove paraffin deposits at different growth stages from petroleum production tubing to evaluate the effects of the descaling parameters on scale removal. A stand-off distance of 25 mm, 50 mm and 75 mm; nozzle arrangement in novel orientations (triangle, diagonal & right-angle) involving 7-nozzles header and chamber pressures (in compression – 0.2 MPa and vacuum -8.0 x10-3 MPa) were utilized as the varying non-hydrodynamically connected parameters. Generally, the selection of both nozzle arrangement and chamber air concentration was found to be governed by the type and shape of the deposit in question while the scale removal capability was found to be reduced with an increase in stand-off distance due to poor jet contact.

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An average hollow shaped paraffin removal of 276 g, 259 g and 226 g were recorded at ambient condition across the respective stand-off distance of the three respective nozzles arrangements. While the introduction of 0.2 MPa compressed air significantly increased the respective removal of the early stage paraffin deposition to 342 g, 299 g and 277 g respectively. Also, more hollow shaped removal improvement of 366 g, 320 g and 288 g were achieved after suctioning the chamber by -0.008 MPa, while simultaneously pumping water at 10 MPa. The case of solid shaped paraffin signifying complete tubing blockage was not effective at ambient condition, with average paraffin removal of 99 g, 126 g and 112 g respectively. However, the introduction of compressed chamber air registered the best solid paraffin removal results of 235 g, 286 g and 256 g respectively. Whereas the suction operation recorded an average removal of 229 g, 270 g and 250 g of paraffin across the respective jet positions and nozzle configurations. This result provides a practical approach to the removal of organic scales deposits at varying descaling conditions of injection pressure, standoff distance and nozzle arrangement.

Keywords: oilfield descaling; High-pressure water jets; nozzle configurations.

1. Introduction

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 and costly interventions to remediate [11]. 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 till date [12]. Such operation is mostly governed by the knowledge of the type, quantity, texture, composition and location of the scale to be removed [3]. Poor planning and inadequate incorporation of scale control strategies (prevention) into the field's asset management cycle during the CAPEX phase, usually done to reduce the running cost of scale removal (OPEX) has been identified as a primary cause of scale deposition [13]. Scale deposition usually occurs before the deployment of inhibition or at the expiration of the inhibition [26] and the entire production system including the reservoir, wellbore & near-wellbore, downhole & downhole equipment, production tubular, wellhead to topside production are at risk of scale deposition when in contact with water during production [20,14]. Scale deposition usually results in flow channels restrictions and downhole equipment damages due to internal abrasion from suspended solid particles [13]. Also, oilfield operations like water flooding enhanced oil recovery promote the deposition of inorganic scales [4] such as calcium and carbonate scales. While organic scale deposit like paraffin and the other aliphatic [29] are more attributed to the dynamic nature of the hydrocarbon production process due to the physicochemical changes of the produced fluids such as pressure and temperature [5]. Although, factors like CO_2 liberation, nature of the surface area of contact, hydrodynamics of the system, and flow regime are also underlying factors [16] as well as the presence of heavy crude in the field. Paraffin scale deposit is also identified as the most predominant scale deposit encountered during production; it has also been characterized as a tasteless, odorless deposit with a density of 900 kg/m^3 that is insoluble in water but soluble in benzene and other esters [10,27]. In the past, the utilization of many unsafe and inefficient scale removal techniques such as the use of aggressive chemical solutions like HCl ([8,28]), destructive mechanical method with explosives [3], replacing the infected tubing by rig workover and even differing production has proven unsuccessful [15]. While the recent wide acceptance of mechanical high-pressure water jetting techniques by multinationals [6] was characterized by backpressure challenges or cavitation effect [7], which unsuccessful compensation with sand particle end up jeopardizing the integrity of the well completions [17]. The introduction of sterling beads in place of sand was excellent but not without the introduction of environmental challenges [2]. Also, the recent single aerated flat fan nozzle approach was characterized by poor scale coverage and high rig time despite recording improvement [1]. Experimental studies on the utilization of multiple high-pressure nozzles in removing different types of scale deposit recently recorded a breakthrough [29] and established some important relationships between hydrodynamic parameters (like the effect of air concentration, increase in injection pressure and the use of multiple nozzles on the amount of scale removed), and some non-hydrodynamic parameters such as the effect of the stand-off distance [29] and nozzle arrangement on the rate of scale removal.

2. Materials

Oilfield wax was simulated by fabricating them from off-the-shelves candles which were melted and cast in a convertible mold (as shown in Figure) to establish the desired shape and type of the wax for the experiment. A combination of Nuclear Magnetic Resonance (NMR) and Infrared analysis (FT-IR) respectively were utilized in investigating the chemical similarities of the household candles to real oilfield paraffin deposit as stated in the work of ([29,30,31] & [32]).

Figure 1: 3D Pictures of assembled wax moulder for (a) Solid, (b) hollow shape [29]

This novel scale removal experimental technique utilizes a multiple nozzle header with three (3) 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 10MPa injection pressure for 3 minutes to remove paraffin scale deposits in the production tubing at different growth stage as shown in Figure 2.

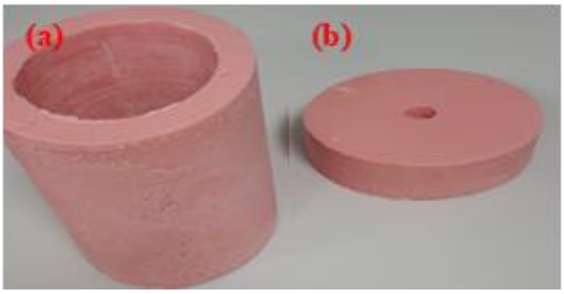


Figure 0: Constructed soft scale (a) hollow shape, (b) solid shaped samples. [30]

The descaling rig, illustrated in **Figure 3,** comprises 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. 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.

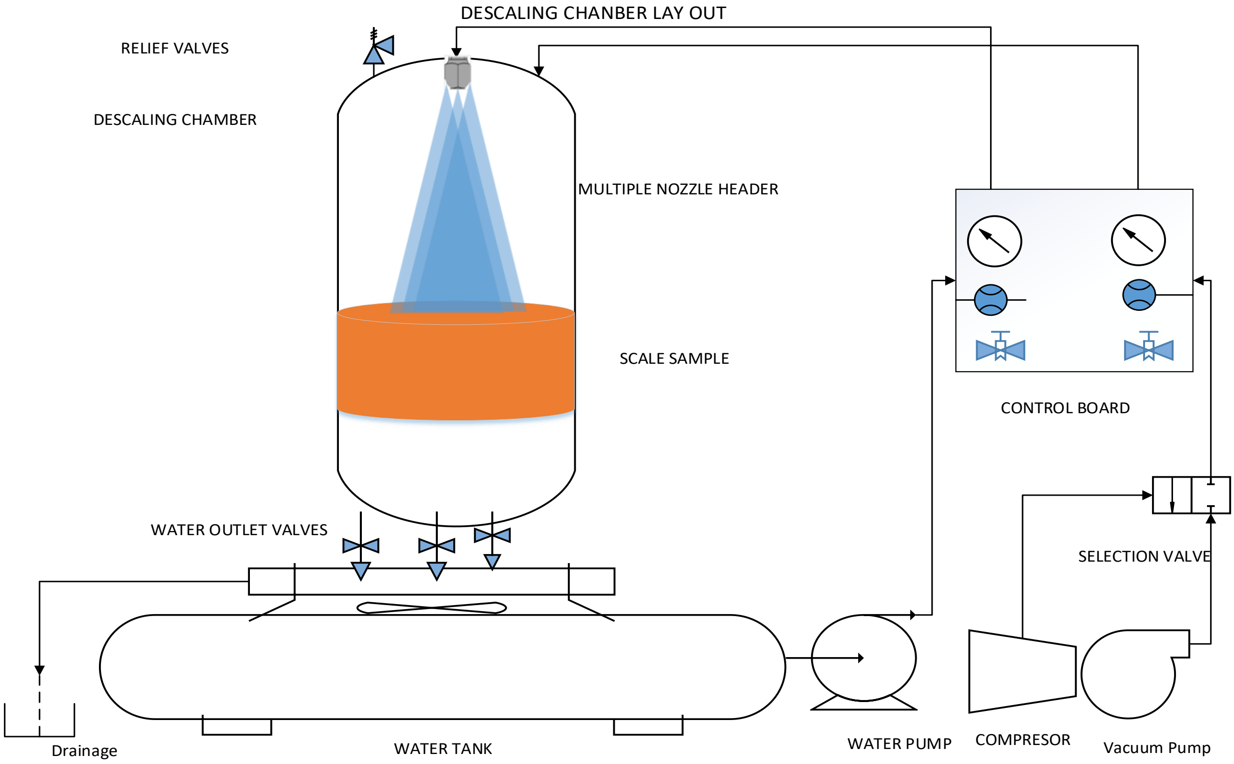


Figure 3: Descaling rig set-up [30]

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 shown in **Figure 4**. This is done to find the most effective distance for removing different types and shapes of scale deposits and at different growth stages.

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

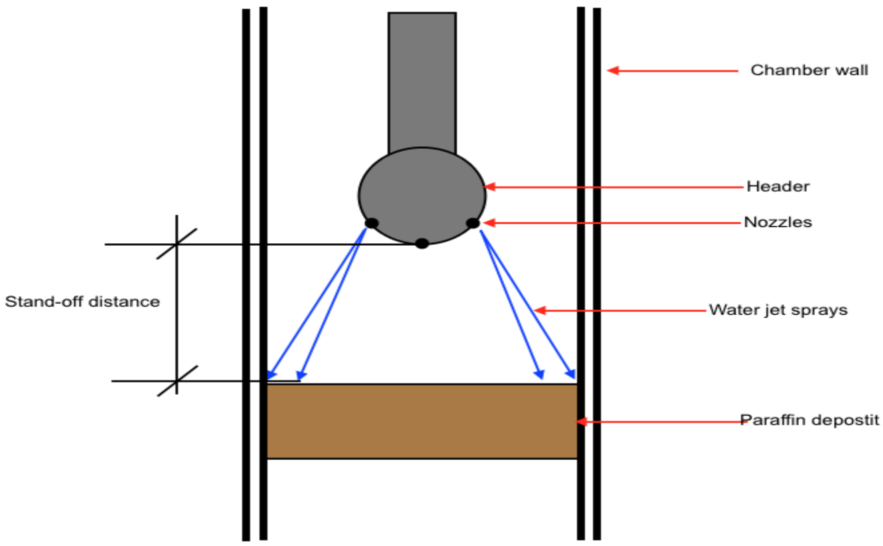


Figure 4: Stand-off distance for solid and hollow paraffin.

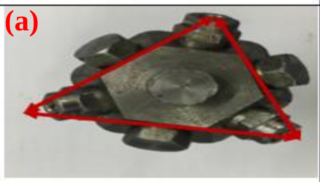
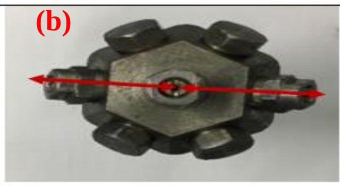
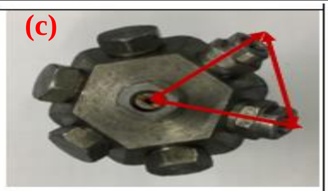
No of Nozzles	Header/Nozzle Configuration		
	Non-Centre Nozzle Configurations (NCN)	Centre Nozzles Configurations (CN)	Centre Nozzle Overlap Configurations (CNO)
3	(a) 	(b) 	(c) 
	Triangle	Diagonal	Right-angled

Figure 5: Header and nozzles arrangements for 3 nozzles at NCN, (b) CN & (c) CNO arrangements

Lastly, the most effective chamber pressure required in cleaning scale deposit of different shapes was investigated. More components of the experimental set-up, the HP and suction pumps are shown in **Figure 6.** 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 0.8MPa respectively.

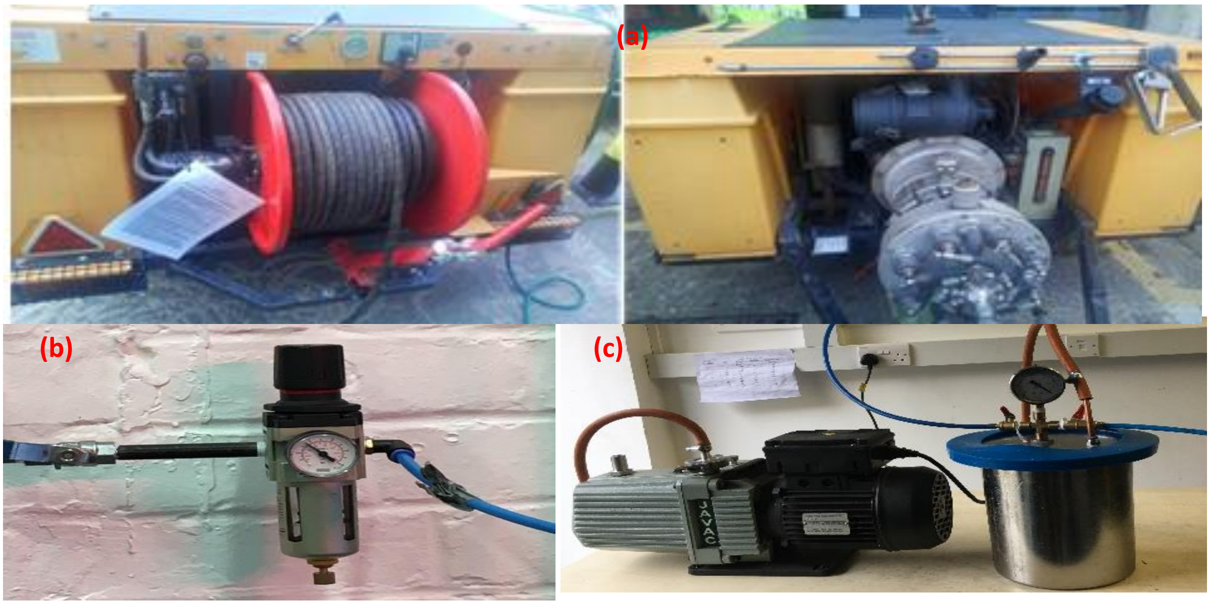


Figure 6: Descaling rig components, (a) high-pressure water pump (b) Compressed air system, and (c) Vacuum pump. [30]

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 [29].
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 10MPa injection pressure.
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. Step i to xi of the experiment were repeated for desired nozzles arrangement (NCN, CN & CNO) respectively.

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

4. Result & Discussion

4.1. Wax characterization.

The nuclear magnetic resonance spectroscopy technique was used to investigate the chemical and compositional representation of the oilfield paraffin in the constructed wax sample. The result confirms the presence of Olefinic protons as shown in Figure . This 1H MNR spectra falls between δ= 0.5 ppm to δ= 1.5ppm and are characterize by Palou and his colleagues [23] as hydrogens of CH, CH_2 and CH_3 groups. While the singlet at δ = 0.0 ppm and δ = 7.278 ppm are attributed to the calibration peak (TMS) and the deuterated chloroform ($CDCl_3$) solvent used in diluting the sample. Furthermore, the presence of saturated hydrocarbon is confirmed by the absence of a peak in the aromatic region of the spectra between δ = 7.0 ppm and δ = 8.0 ppm.

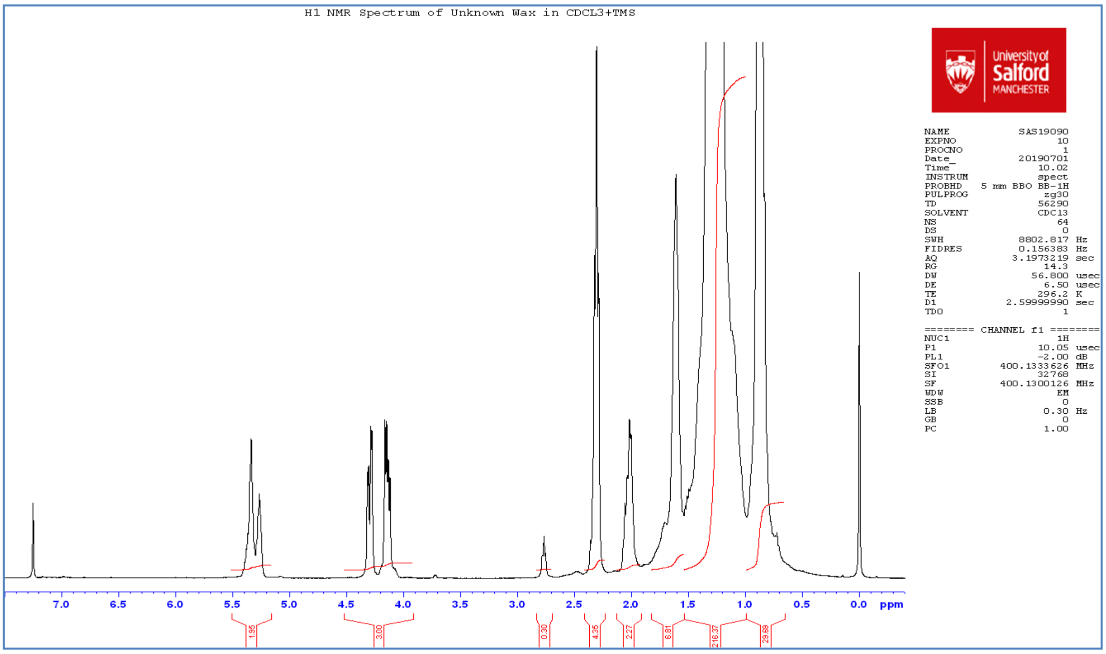


Figure 7: NMR result of soft scale sample [29]

Further subjection of the constructed wax sample to infrared spectroscopy analysis using the Thermo Scientific Nicolet iS10 for the confirmation of the NMR result and re-affirmation of its chemical composition of the oil field scale deposit (paraffin) proved positive. Also, by superimposing the FT-IR result with the absorption peaks of paraffin flaxes from the National Institute of Standard and Technology (NIST) database, a match was obtained. This further confirms that the scale samples possess similar fingerprints and bands of paraffin functional groups. The results are shown in Figure . The presence of aliphatic hydrocarbons was affirmed in the sample due to the presence of absorption peaks between 2900 cm-1 and 2800 cm-1 that is usually allocated for stretching and vibrations of CH_2 and CH_3 [19]. While more validation and re-affirmation of the chemical and compositional similarities of the oil field paraffin properties in the constructed wax was achieved after superimposing the FT-IR result with that of paraffin liquid as shown in Figure .

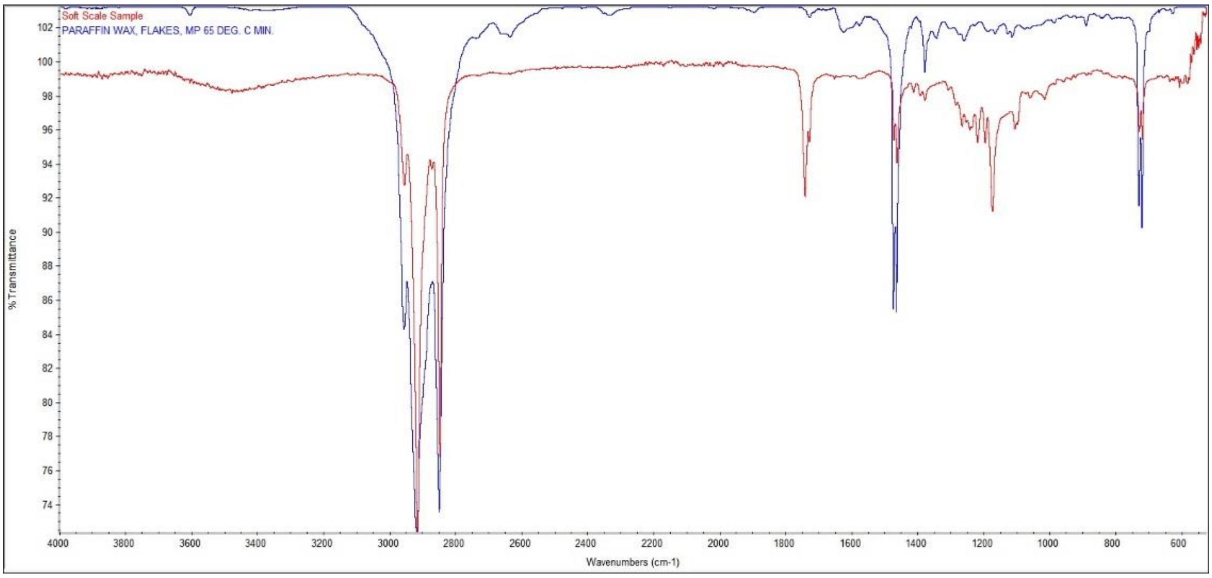


Figure 8: Infrared analysis compared to paraffin flakes from the NIST database. [30]

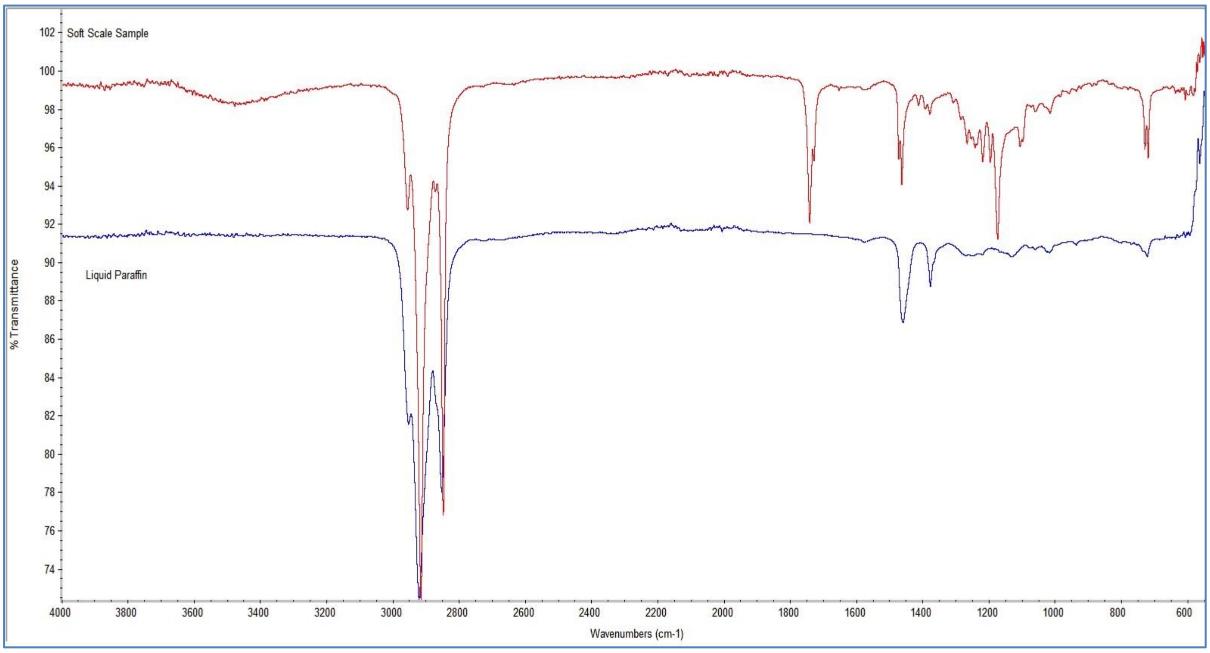


Figure 9: Infrared analysis compared to liquid paraffin. [29]

4.2. Descaling performance evaluation

The descaling result archived from the publication titled Experimental Removal of Paraffin Scale Deposit from Petroleum Production Tubing Using Multiple High-Pressure Nozzles [29] 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. These terms are said to be non-hydrodynamically connected as they have no affiliation to the mass flow rate of the spray. 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 [25] prompting the need for unique descaling conditions that are connected to their physical properties.

4.3. Optimum standoff distance determination

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 in respective 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]. 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.

4.4. 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 [18,9]. 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 [32]. This can be attributed to the absence of an 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 incomplete of tube 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 [30]. Also coupled with the highest droplet velocity concentrating toward the centre of spray overlap region [21] that was distrusted. However, the introduction of the centre nozzle in both CN and CNO arrangement for the removal of early and complete deposit in production tubing was found inefficient, and not suitable throughout the experiment.

4.5. 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 [31]. 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. 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 as shown in equation 1. 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 2 & 3, 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. 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 shown in equation 1 and 3. Were P being internal resultant pressure (chamber pressure+ jet pressure), r, is the radius of the hollow sample t, is its thickness, and D is the diameter of the sample.

$$\frac{Pr}{t} = \tau_{hoops} \quad (1)$$

$$\tau_{hOOPS\,Vac} > \tau_{hOOPS\,Amb} > \tau_{hOOPSComp} \quad (2)$$

$$\frac{D}{t} > 20 \quad (3)$$

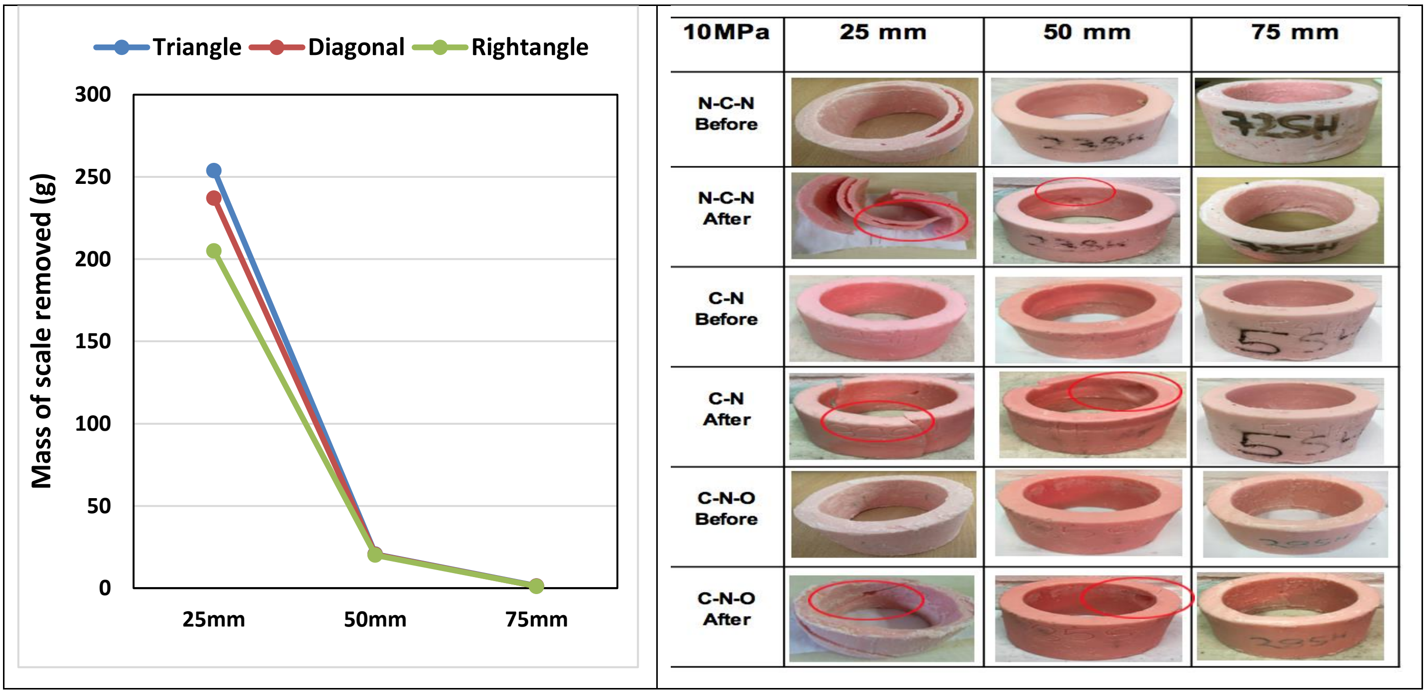


Figure 10: Descaling results of hollow shaped paraffin scale deposits in the ambient chamber condition

Although, 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 [25]. 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 3. 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) [22]. 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 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.

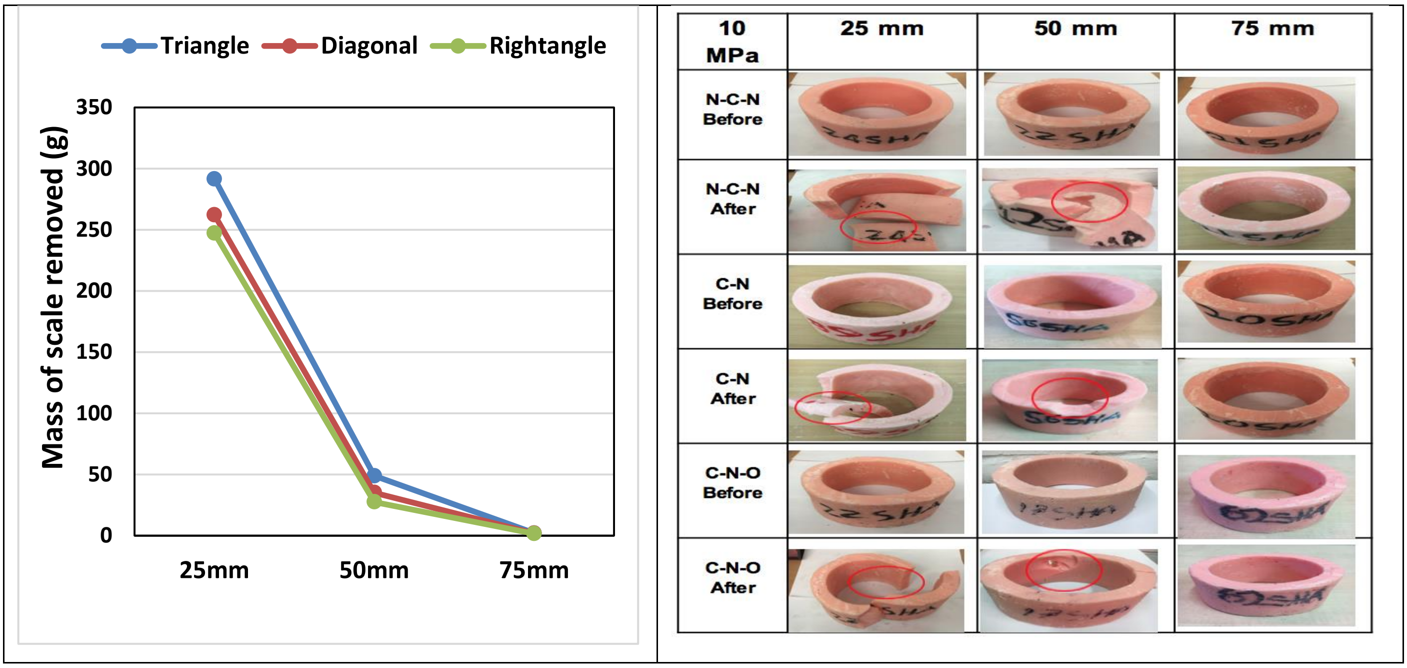


Figure 11: Descaling results of hollow shaped paraffin scale deposits in the compressed chamber condition

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** 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**. 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.

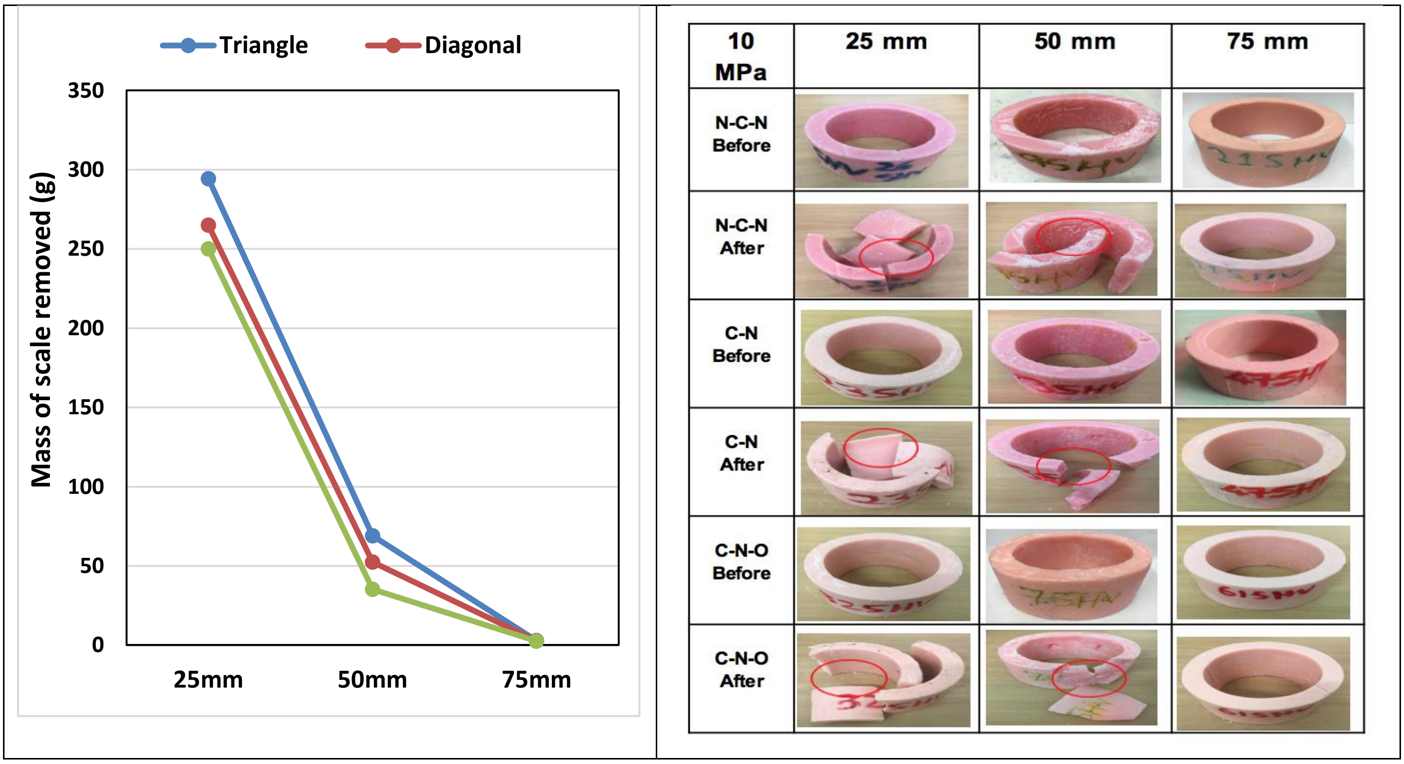


Figure 12: Descaling results of hollow shaped paraffin scale deposits in the vacuumed chamber condition

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** . 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** . 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** . The NCN triangle nozzle arrangement is still the tip to be most effective among others. As a total removal value of 217g deposit removal 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** 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.

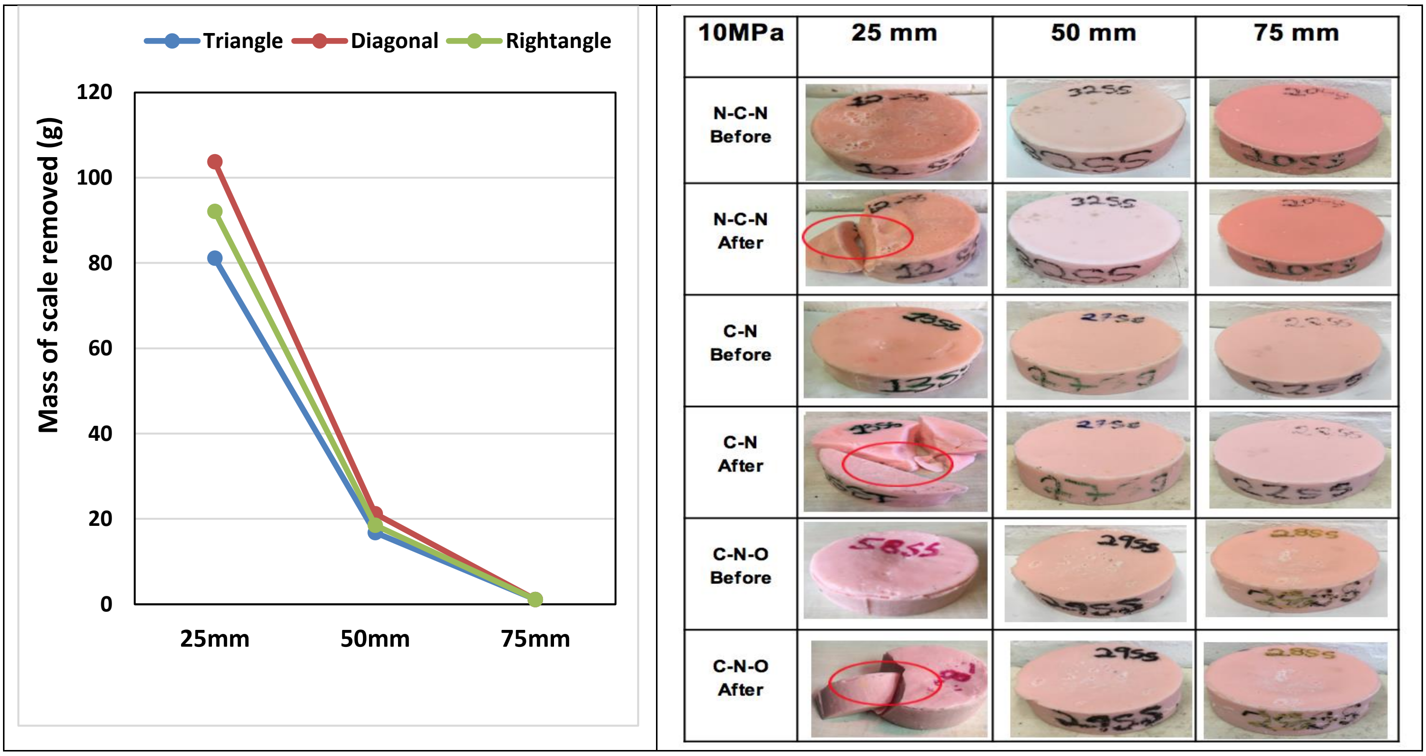


Figure 13: Descaling results of solid shaped paraffin scale deposits in the ambient chamber condition

Figure , **Figure** & **Figure 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 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** showcase a poor uniform erosion across the board for the75mm 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** 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.

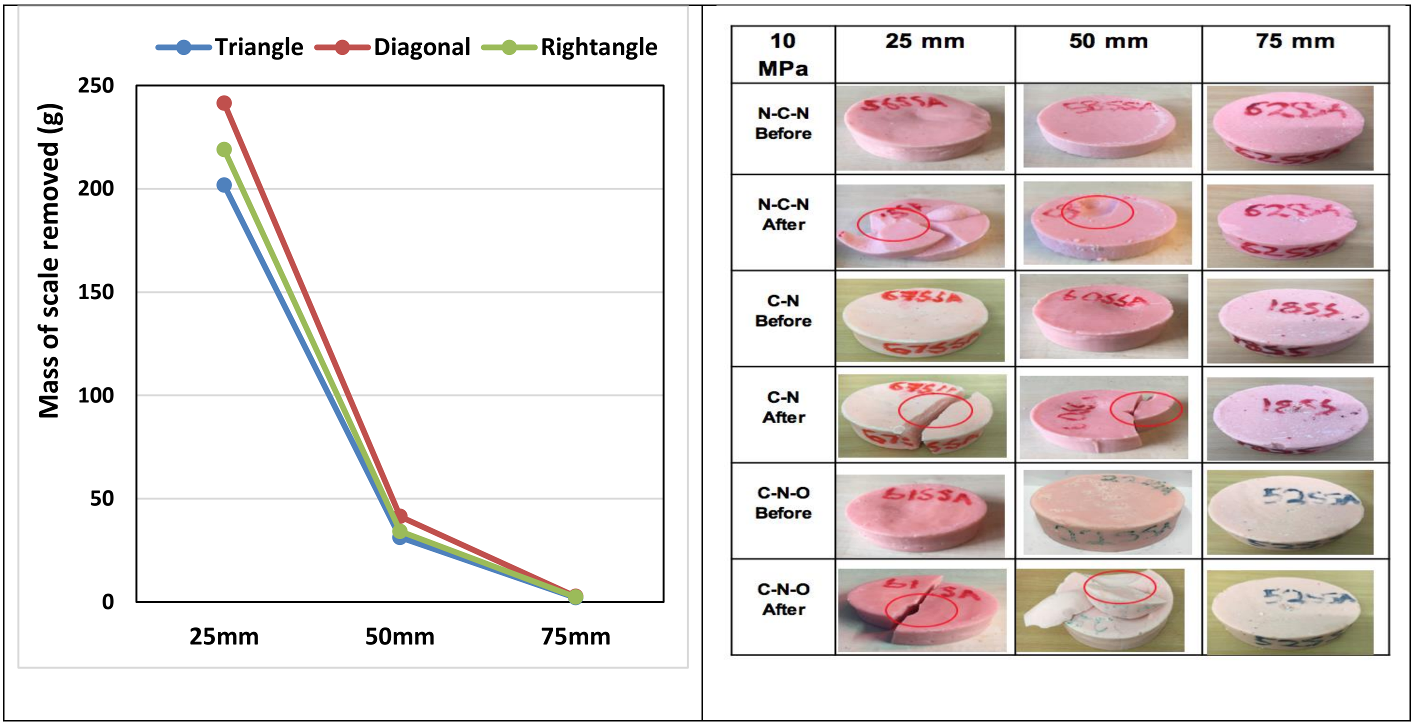


Figure 14: Descaling results of soli shaped paraffin scale deposits in the compressed chamber condition

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** , 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** . The 75mm jetting position, as usual, produce a very poor average descaling result (2.4g) that is not responding to another descaling parameter 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** . 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.

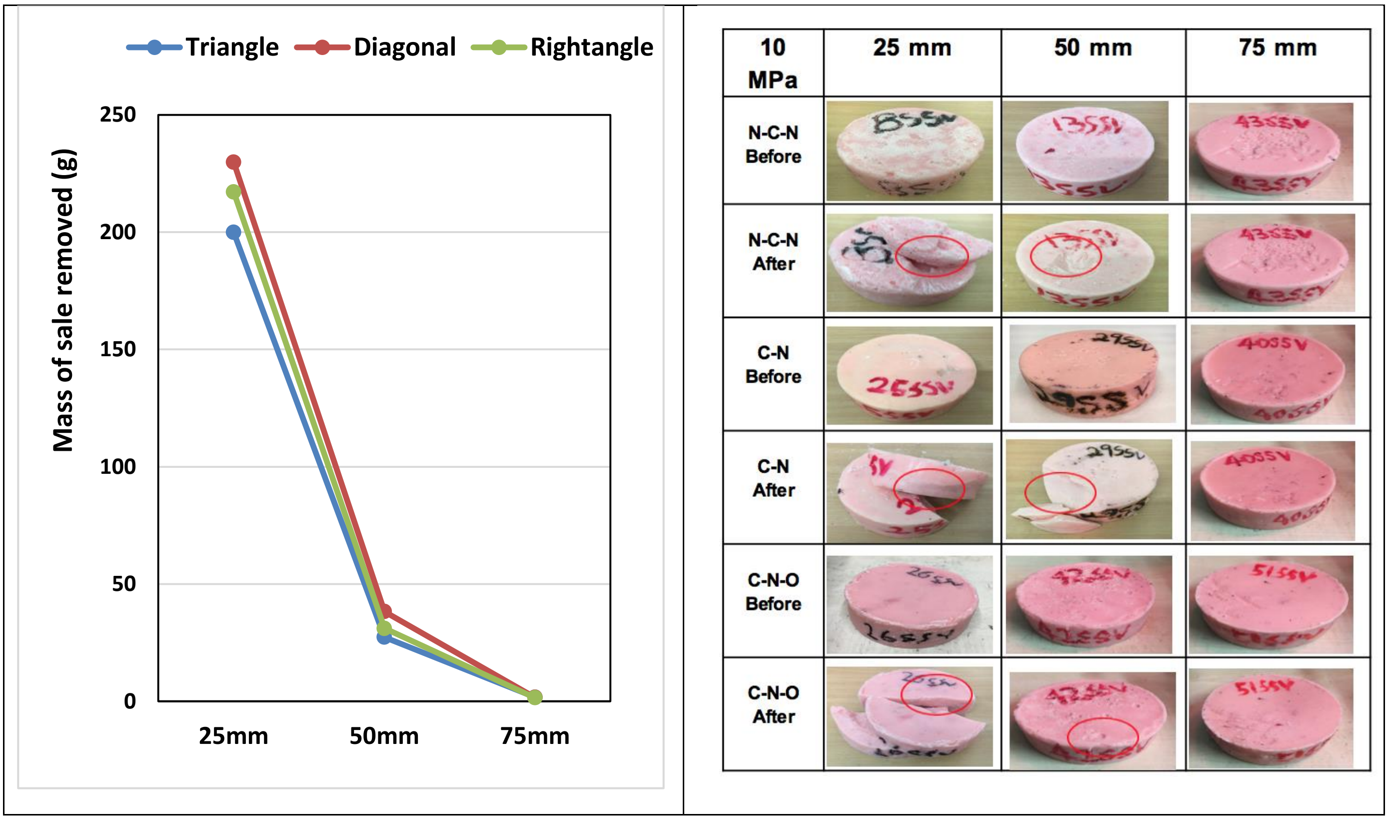


Figure 15: Descaling results of solid shaped paraffin scale deposits in the vacuumed chamber condition

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 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 an almost 31g increase and material breakage in CN arrangement as shown in **Figure 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 15**. While at 50mm distance, a significant average removal difference of 7g and 11 were observed between CN and CNO &CN and the entire results of the 75mm distance poorly (0.1g) responds to the nozzle arrangement alteration parameter as shown in Figure 15.

5. Conclusion

Generally, the experimental results established a trend that linked the increases in the amount of scale removed to a reduction in the downstream distance between the nozzle header and the wax sample which is compensated with the right nozzle arrangement selection that relies on the shape of the scale deposit in question. Having inferred the foregoing, some conclusions can be drawn as thus;

- The far downstream jetting position was found not responding to other jetting parameters like nozzle arrangement and chamber pressure due to poor jet target contact and spray breakup distance phenomenon.
- So, also the selection of chamber pressure condition was found to depend on the shape of the descaling candidate and the centre nozzle arrangement are more suitable for cleaning complete block tubing, while the absences of centre nozzle suite partial tubing blockaded cleaning.

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