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An experimental approach to the descaling of production tubing using high pressure flat fan nozzles

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The mechanical approach of utilizing high-pressure water for scale removal has gained wider acceptance by multinationals despite facing poor downhole performance challenges (cavitation) that need abrasion compensation (sand) with side effect of jeopardizing the integrity of the well completions. The replacement of sand with sterling beads was excellent with good post descaling well completion integrity at the expense of environmental complexity. While the recent single nozzle, solid free aerated jetting descaling technique was characterized with poor scale coverage and high descaling time. This investigation presents the novel technique of scale removal utilizing multiple high-pressure flat fan nozzles at different distances, nozzle configurations and injection pressure to remove soft scale sample made of paraffin. The scale shaped in two different patterns of hollow and solid signifying different growth stages of paraffin in production tubing. The results at 25 mm stand-off distances showed that the scale removal was within the range of 0.8 to 42.8 g (for hollow shape scale) and 0.3 to 5.2 g (for solid shape scale) at 4.8 MPa with different nozzle configurations. Increasing the injection pressure to 6 MPa removed more scale within the range of 1.1 to 93.7 g (for hollow shape scale) and 0.7 to 7.3 g (for solid shape scale). Moreover, at 10 MPa injection pressure the scale removal was within the range of 1.1 to 253.8 g (for hollow shape scale) and 1.1 to 103.7 g (for solid shape scale). This result will provide a practical approach to the removal of organic scales at varying descaling conditions of injection pressure, standoff distance and nozzle configurations.

Key words: Scale removal, multiple nozzles, high-pressure water spray, flat-fan nozzle.

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

in (Yusuf et al., 2016). Additionally, petroleum products are produced and transported from the reservoir to the surface via pipelines and other flow channels (Mansoori et al., 2014; Nejad and Karimi, 2017). Consequently, production system such as wellbore and near-well bore,

downhole and downhole equipment, and processing facilities (e.g. pump, separators, heat exchangers, etc.) become prone to scale deposit since they are constantly in contact with produced water during production from the field (Guan, 2015) production systems such as wellbore and near-wellbore facilities, downhole and downhole equipment, and processing facilities (e. g. like pumps, separators, and heat exchangers, etc.) become are prone to scale deposition since because they are constantly in contact with produced water during production from the field (Guan, 2015). These flow channels often most time suffers flow restriction and other damages due many petroleum production problems especially from production associated problems like scale deposition solid deposition of scale deposit that lead to internal abrasion by suspended particles (Ghouri et al., 2018; Peng and Guo, 2017) production tubing serves as both the main production conduit as well as the only access for remedial and maintenance programs such as well logging in (Yusuf et al., 2016). Additionally, petroleum products are produced and transported from the reservoir to the surface via pipelines and other flow channels (Mansoori et al., 2014; Nejad and Karimi, 2017). Consequently, production system such as wellbore and near-well bore, downhole and downhole equipment, and processing facilities (e.g. pump, separators, heat exchangers, etc.) become prone to scale deposit since they are constantly in contact with produced water during production from the field (Guan, 2015).production systems such as wellbore and near-wellbore facilities, down hole and downhole equipment, and processing facilities (e.g. like pumps, separators, and heat exchangers, etc.) become are prone to scale deposition since because they are constantly in contact with produced water during production from the field (Guan, 2015). These flow channels often most time suffers flow restriction and other damages due many petroleum production problems especially from production associated problems like scale deposition solid deposition of scale deposit that lead to internal abrasion by suspended particles (Ghouri et al., 2018; Peng and Guo, 2017). Scale deposition results from mineral deposit on production tubing and other components due to produced water saturation. Scale deposition results from solid minerals deposit on production tubing and other components due to produced water saturation precipitation from produced water at conditions that make them unstable in the produced water solution. Although the process controlled by changes in thermodynamic conditions in the tubing, poor planning and inadequate incorporation of scale control strategies into the field's asset management cycle contribute to escalation escalates of scale deposition. Although the process is mainly controlled by changes in thermodynamic conditions in the tubing, poor planning and inadequate incorporation of scale control strategies into the field's

assets management cycle contribute to the escalation of scale deposits cause increases in scale deposition (Farrokhrouz and Asef, 2010). Even though, deposition may occur either before the deployment of inhibition or at the expiration of the inhibition Scale inhibitors are usually employed to prevent it. Therefore, Even though, scale depositions may occur either before the deployment of inhibition or at the expiration of the inhibition (Smith et al., 2000), limiting the treatment options to confrontation emergency (cure) removal that need to be done in a fast and safe manner.., limiting the treatment options to confrontation emergency (cure) removal that needs to be done in a fast and safe manner.

Many reservoir minerals, depending on the reservoir chemical characteristics and oil recovery techniques utilized utilized, are responsible for oil field scale deposits on production depositions (Esbai and Palanisamy, 2016). However, calcium carbonate, calcium sulfates and barium sulfates are the most predominant scale deposit and are t. These minerals are minerals being are term referred to as inorganic or mineral scales (Zahid, 2015). In addition, organic scale 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 (Zahid, 2015). Also, similarly, deposition of organic scales, which include such as aliphatic and paraffinic hydrocarbons, and paraffin is attributed to the dynamic nature of hydrocarbon production processes. In other words, organic scales deposition is also influenced by as a result of physicochemical and thermodynamic (volume, temperature, PH and pressure) changes in properties of the produced fluid. Scale deposition can occur (volume, temperature, pH and pressure), which can deposit at any part of the production system (Armacanqui et al., 2016). Sometimes organic scale deposition is directly connected to the heavy crude production nature of a field that is somehow globally distributed. Nevertheless, other important scale deposition influencing factors include produced water properties, CO_2 liberation, nature of the surface, hydrodynamics of the system and flow regime (Heydrich et al., 2019) should not be underrated.

Paraffin scale deposits predominate dominate 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 Tao et al. (2017), paraffin characterized paraffin as having has 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.

Many inefficient and unsafe scale removal techniques like the destructive mechanical method (that is, with that is, explosives) (Alabdulmohsin et al., 2016), the use of
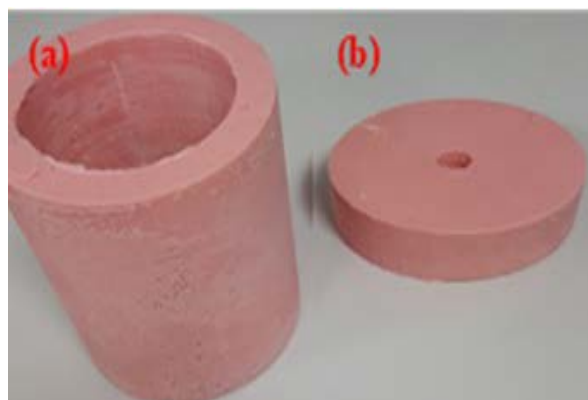
Figure 1. Constructed soft scale sample, (a) Hollow Shape and (b) Solid Shape.
Source: Yar'Adua (2020).

aggressive chemical solutions such as like HCl (Hamdy et al., 2014; Vazirian et al., 2016), rig work over to replace the tubing and even differing of production haves unsuccessfully been tried in the past (Guimaraes et al., 2008). Although recently, the mechanical high-pressure water jetting techniques has been widely accepted by the multinational (Bajammal et al., 2013), despite facing back pressure challenges (cavitation). But in recent times, the mechanical or high-pressure water jetting techniques have been widely accepted by the multinational Oil and Gas Industry (Bajammal et al., 2013), despite facing back been associated with back pressure challenges (like cavitation). The introduction of sand particles in the descaling fluid (slurry) (abrasion) by Crabtree et al., ((1999) seems to improve the performance, however, but at the expense of the integrity of the well completions. Additionally, the replacement of sand with sterling bead by Jauregui et al. (2009) was impressive but with more environmental complexity. Similarly, the replacement of sand with sterling beads by Jauregui et al. (2009) was impressive but with more environmental complexity not without creating further environmental degradation issues. While the While the recent introduction of the single high pressure aerated flat fan approach by Abbas et al. (2016) was successful. It is, however, characterized by poor scale coverage and high rig time.

EXPERIMENTAL PROCEDURE

The scale removal technique investigated in this study subjects the scales to multiple high-pressure room temperature pure water sprays at different injection pressures of 4.8, 6.0 and 10 MPa for 3 min experimental run time using multiple flat-fan nozzles to clean production tubing of soft scale (paraffin) deposits as reported by (Yar'Adua et al., 2020, 2021).. It however, extends the range of investigation of the work of Yar'Adua et al. (2020) by simulating a fully blocked production tubing with the introduction of the so-called solid scales (Figure 1) and the use of different arrangements of the

nozzles. The scale specimens were constructed from off-the-shelf, household candles for the experiment due to scarcity and preservation difficulties of real oilfield organic paraffin scale deposits. While chemical compositional analysis, were carried out to examine their chemical compositions and establish their similarities to real oilfield organic scale deposits using Fourier-Transformed Infrared spectroscopy (FTIR) and Nuclear Magnetic Resonance (NMR).

Overview of the basic experimental procedure is described in the work of Yar'Adua (2020), where ambient temperature water was utilized during the experiment.

The descaling rig, shown in Figure 2, comprisesing the a high-pressure water pump and a descaling chamber housing the multiple spray header and the scale depositspecimen. The experiment was conducted, was utilized at ambient temperature and pressure condition for the experiment.

Scale deposit was removed at the different injection pressures (stated above) mentioned earlier and at different downstream stand-off- distances of 25, 50 and 75 mm. The stand-off-distance, in this context is the vertical distance from the exit orifice of side nozzles to the surface of scale deposits (Yar'Adua et al., 2020) as shown in Figure 3.

Additionally, different numbers of nozzles were fitted into the multiple nozzles header at different nozzles arrangements to find the efficient nozzle configuration for optimal removal of different types of scale deposits from petroleum production tubing. Also, both the nozzle configuration and arrangements were done simultaneously by fitting into the nozzle header the desired numbers of nozzles (3, 4 and 5) at different nozzles arrangements. The configurations for the different nozzles arrangements were termed Non-Center Nozzle (NCN), Centre Nozzle (NC) and Center Nozzle Overlap configurations. While blank plugs were used to block the undesired header nozzle socket (Figure 4). Furthermore, the experimental procedure for the effect of the number of nozzles on injection pressure was investigated using the bucket weighing experiment and detailed in the work of (Yar'Adua et al., 2020).

RESULTS AND DISCUSSION

As earlier mentioned that, the constructed wax scale deposits specimens were chemically and compositionally characterized to determine their true representation
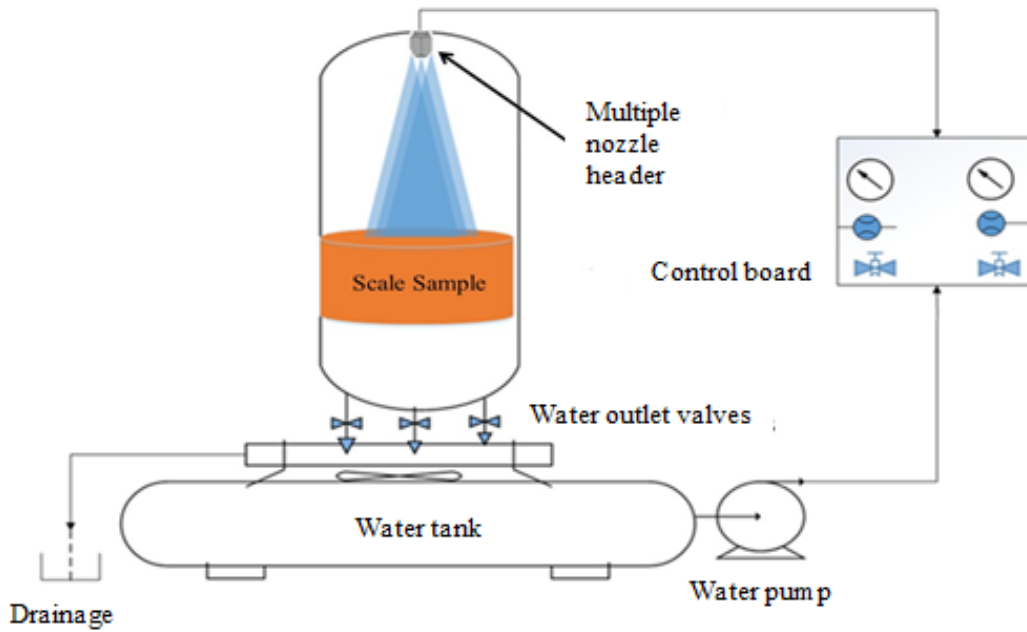
Figure 2. Schematic diagram of the descaling setup.
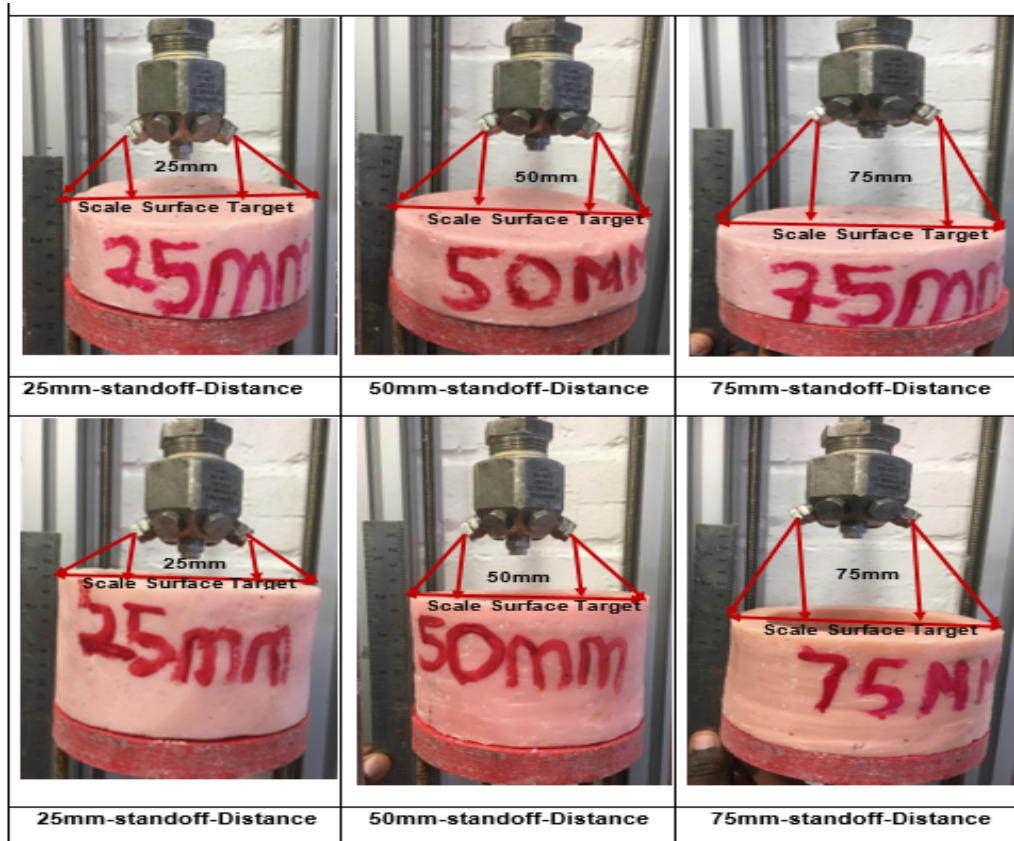Source: Yar'adua (2020).

Figure 3. Downstream distances of different nozzle arrangements.
Source: Yar'Adua (2020).

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

Figure 4. Nozzle arrangements for 3, 4 and 5 nozzle at (NCN), (b) (CN) and (c) (CNO).
Source: Yar'Adua (2020).

representativeness of oilfield organic scale deposits using the combination of NMR and FT-IR analysis techniques. THE 1H NMR spectra generated from NMR spectroscopy as expressed in Figure 5 confirmed the presence of Olefinic protons between δ = 0.5 and δ = 1.5 ppm, that are usually described as hydrogen groups of CH, CH2 and CH3 (Palou et al., 2014), in the constructed scales specimens as previously reported by (Palou et al., 2014). Also, this is more supported. Also, this is more supported with non-observance of any peak at the aromatic spectra region of δ = 7.0 and δ = 8.0 ppm. While singlet at δ = 0.0 ppm and the extreme peak singlet (δ = 7.278 ppm) are more associated to the TMS calibration and the deuterated chloroform solvent (CDCl3) used in dissolving the deposit.

Further subjecting the constructed scale specimens to FTIR analysis using the Thermo Scientific Nicolet iS10 spectroscopy revalidated the NMR analysis findings. Furthermore, s and subsequent super impositionng of the FTIR generated spectra with the retrieved paraffin flaxes results obtained from National Institute of Standard and Technology (NIST) database of FT-IR showed impressive qualitative and quantitative matches (Figure 6). More so, the matched spectra's reveals similar bands and fingerprints with absorption peaks between 2900 and 2800 cm-1 that is normally assigned to vibration and stretching of CH2 and CH3 functional groups of aliphatic paraffin (Manoj et al., 2012) as shown shown in Figure 6.

The matched spectra's reveals similar bands and fingerprints with absorption peaks between 2900 cm^{-1} and 2800 cm-1 that is normally assigned to vibration and stretching of CH2 and CH3 functional groups of aliphatic paraffins (Manoj et al., 2012) as shown in Figure 6.

Even though both deposits share similar chemical properties, they may still have to respond to different jetting mechanisms due to their differences in shapes and sizes (Zongyi, 2004), making them require unique descaling conditions that are related to their physical properties. The effect of varying injection pressure that which is connected related to the kinetic energy of the spray by direct proportionality with the jet impact or spray velocity, has played plays the most vital role in removing all the scale types. Equations 1 and 2 throw more light on this assertion:
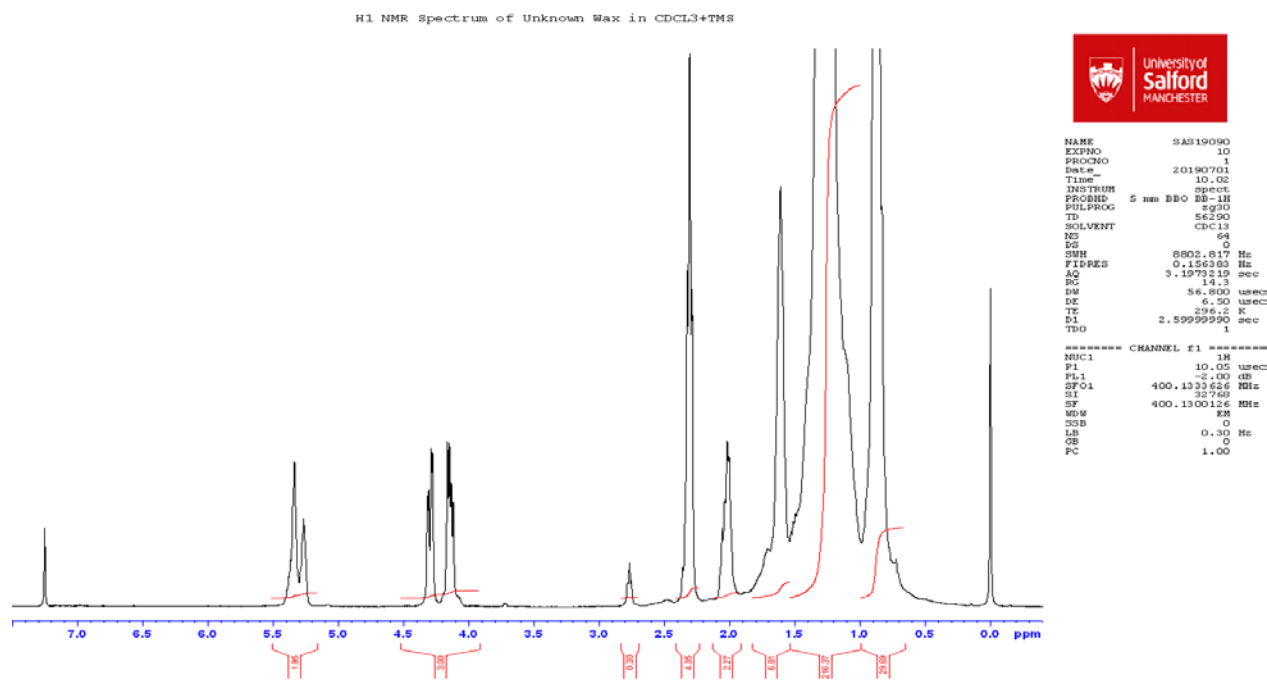
H1 NMR Spectrum of Unknown Wax in CDCL3+TMS

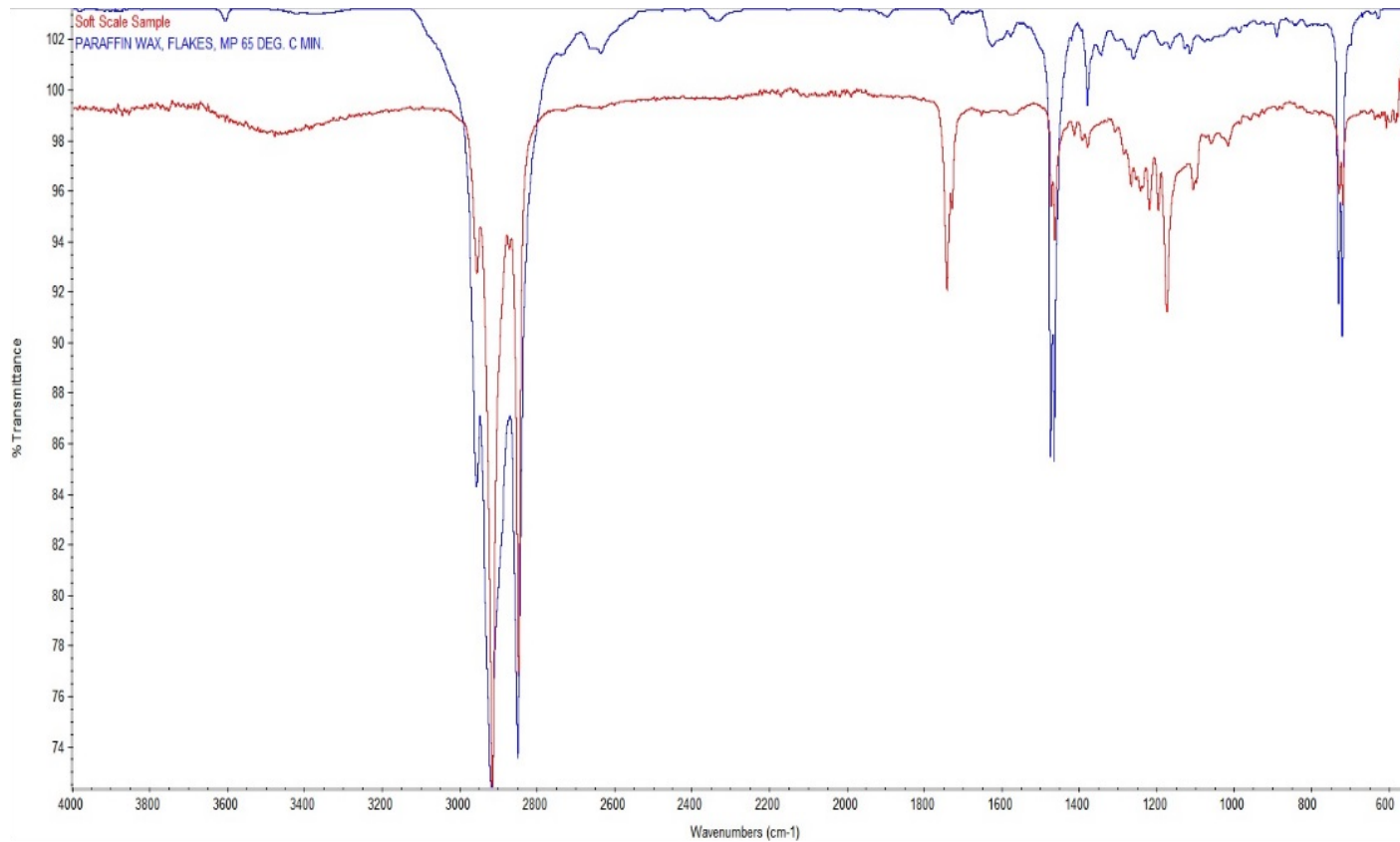**Figure 5.** NMR result of constructed scale specimens.

Figure 6. FTIR analysis results of scale specimens superimposed with **NIST** FTIR of Paraffin flakes.
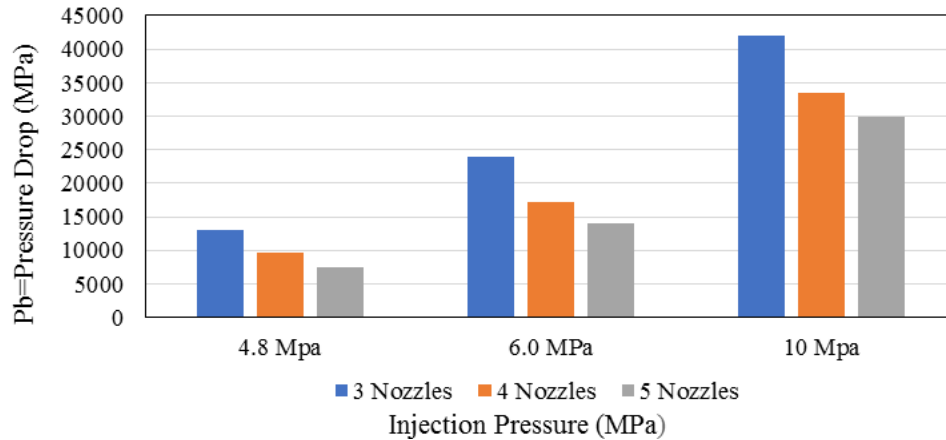
Figure 7. Bucket weighing analysis results.

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

$$P_d = \frac{1}{2}mV^2 \qquad (2)$$

where P_t is the total pressure, P_d is the dynamic pressure or the injection pressure and P_s is the static pressure, making the difference between static pressure and the stagnation pressure to be equal to the dynamic pressure (injection pressure) represented as the kinetic energy per unit volume of a fluid particle.

In agreement with past works (Abbas et al., 2013; Yar'Adua et al., 2020), it was observed that the amount of scale removed increases as the stand-off distances decreases. In all cases, spraying the samples from 25 mm stand-off distance yielded the best result while the extent of scale removal decreased by moving the sample to 50 mm and subsequently to 75 mm. This is because increasing the downstream distance resulted in producing very poor removal results due to reduction in the jet impacts on the scale specimens and complete jet profile constrain (Opfer et al., 2013). Nonetheless, far jetting positions of 50 and 75 mm distance were able to effectively break the samples as a result of good nozzle arrangement selection. This indicates that the effectiveness of scale removal using the technique of this study is not only dependent on the stand-off distance but also the nozzle configurations.

The numbers of nozzles and nozzle configuration are major determinants of the jet impact that account for the scale removal. The number of nozzles is proportional to the jet flow rate and injection pressure but inversely proportional to the area of the nozzle orifice due to pressure drop effect. Meaning that, the fewer the nozzles, the greater the pressure drops that will be produced and consequently, the higher the jet impact velocity (kinetic energy) that will be available for scale removal (Tian et al., 2009). Even though, the more the number of nozzles,

the larger the scale deposits coverage due to spray overlap effect.

The effect of pressure drops across multiple nozzles is expressed in Equations 3 and 4 and graphically shown in Figure 7, after imputing the generated flow rate results of the bucket weighing experiment into Equation 3.

$$P_b = \frac{513.559Q^2 p}{A^2 C^2} \qquad (3)$$

where P_b is the pressure drop (MPa), Q is the flow rate (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 (0.5 mm × number of nozzles)

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

To achieve effective descaling results, maximum target surface coverage is an essential requirement. In addition to that, the appropriate nozzle arrangement selection for the shape of the scale growth stage and optimum jet impact pressure must be set (Chimagwu et al., 2012; El Khamki et al., 2010; Enyi et al., 2012). In this study, the non-centre nozzle arrangement (NCN) demonstrated suitability in removing early-stage growth of paraffin deposits in production tubing as a result of the jet impact being diverted to the side nozzles that are in good contact with paraffin surface. The results of center nozzle arrangement (CN) showed to be more efficient in the removal of complete paraffin scale tubing blockage as a result of introduced center nozzles spraying directly on the surface of the scale and having more kinetic energy than the side nozzle, coupled with better particle abrasion and lifting capacity. Furthermore, center nozzle overlap arrangement (CNO) is also preferable in removal of complete tube blockage, although it is less effective than the CN arrangement due to complete spray overlap jet
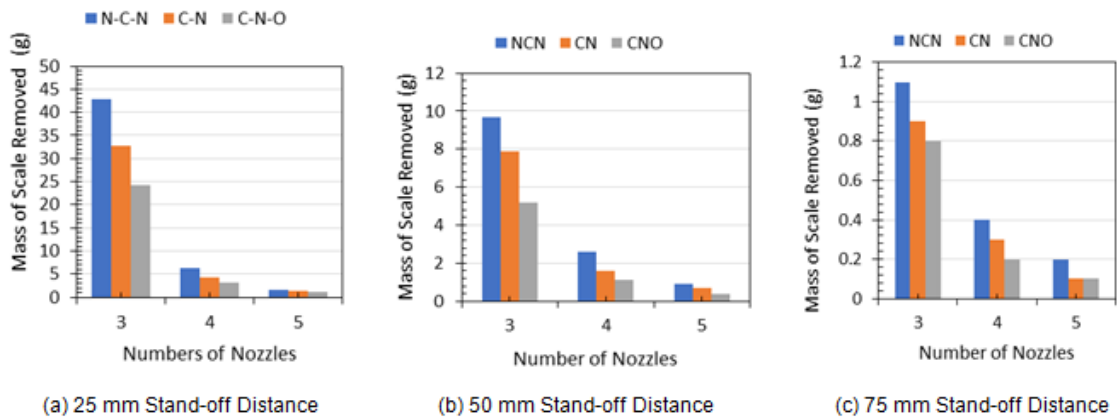
Figure 8. Hollow paraffin deposit removal at 4.8 MPa from (a) 25 mm, (b) 50 mm and (c) 75 mm distance.
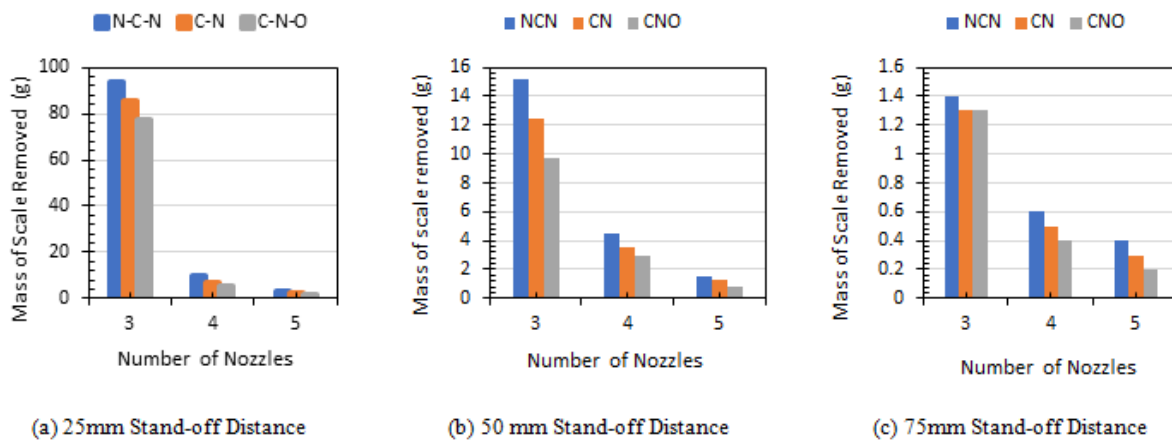

Figure 9. Hollow paraffin deposit removal result at 6.0MPa from (a) 25 mm, (b) 50 mm and (c) 75 mm distance.

profile constraint as a result of the tubing that end up getting sprayed instead of the deposit. In addition to the highest droplet velocity concentrating toward the center of spray overlap region (Nourian et al., 2011) that was distrusted. However, it should be noted that the introduction of center nozzle in both CN and CNO arrangement for hollow shape scale presented inefficient scale removal result and makes them not suitable for removing early stage paraffin deposit from production tubing (Yar'Adua et al., 2021).

Generally, the removal rates of the hollow shaped paraffin deposit across all the combination of techniques were 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 (Raju et al., 2015) as shown in

Equations 5 and 6, where P being the internal resultant pressure (chamber pressure + jet pressure) while r, D and t are the radius, diameter and the thickness of the sample, respectively.

$$\frac{Pr}{t} = \tau_{hoops} \tag{5}$$

$$\frac{D}{t} > 20 \tag{6}$$

As shown in Figure 8 to 10, increasing the stand-off distance reduces the mass of scales removed. Also, at each downstream distance (25, 50 and 75 mm), increasing the injection pressure resulted in increase in the amount of scale removed, although the removal rate reduces with increase in number of nozzles. Furthermore, as explained previously, for hollow shape scale, the results from NCN arrangement shows better efficiency
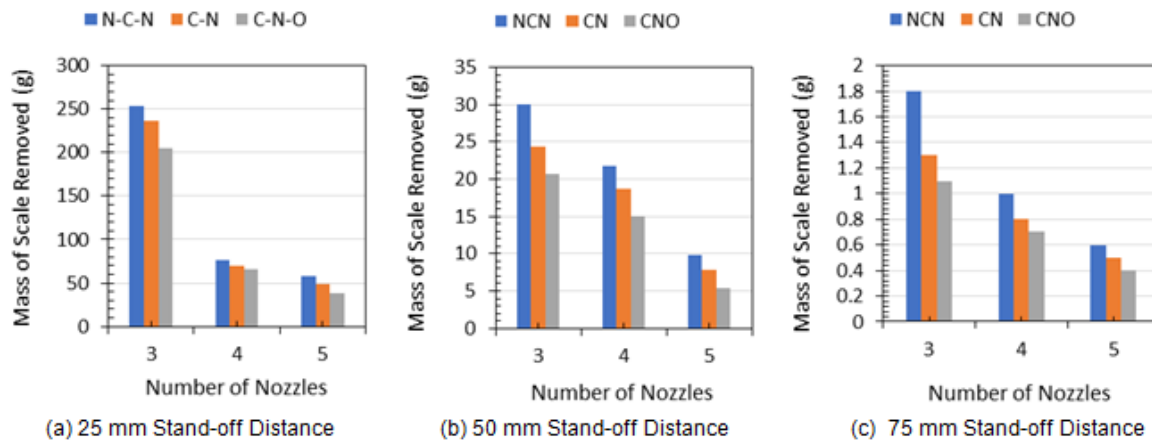
Figure 10. Hollow paraffin deposit removal result at 10 MPa from (a) 25 mm, (b) 50 mm and (c) 75 mm stand-off distance.

compared to CN and CNO nozzle arrangements.

Meanwhile, results from the investigation of the effect nozzles configurations in terms of numbers of nozzles (3, 4 and 5), nozzles arrangement (NCN, CN and CNO), coupled with altering injection pressure (4.8, 6.0 and 10 MPa) and stand-off distance (25, 50 and 75 mm) toward hollow scale removal are presented in Figures 8 to 10.

Figure 8a quantitatively demonstrated an initial scale removal of 2.9, 2.3 and 1.8%, respectively across the NCN, CN and CNO nozzle arrangements when spraying at 4.8 MPa from 25 mm distance with 3, 4 and 5 nozzles, respectively. Effect of altering nozzles configuration is more evident with lesser nozzle count (3 nozzles), due to pressure drop effect (Shen, 1998). An additional increase in scale removal of 4.5 g from 1.7 g was recorded after reducing the number of the nozzles from 5 to 4 nozzles while an increase of 41.1 g recorded a result of further altering the nozzle configurations from 4 to 3 nozzles at the same 4.8 MPa from 25 mm distance with NCN arrangement. Additionally, Figure 8b and c shows similar descaling trends with that in Figure 8a, although with almost 70% reduction in removal rate across all the descaling combinations as a result of moving the atomizers 25 mm distance further away from the scale target. While further increasing the jetting position to 75 mm yielded a very poor removal as a result of poor jet-to-target contact.

Also, at 6 MPa injection pressure and 25 mm distance, Figure 9a demonstrated a 24.6, 21.2 and 18.1% removal of paraffin across NCN, CN and CNO arrangement, respectively. A linear increase in scale removal of 50.9, 3.2 and 0.6 g was also observed after increasing the injection pressure from 4.8 to 6.0 MPa crossed the NCN nozzles arrangement of 3, 4, and 5 nozzles configurations respectively, with a similar trend for the other arrangements due to increase in the kinetic impact of the jet. The consequence of altering nozzle configurations doubled the paraffin scale removal by 7.1 g from 2.9 g and subsequently by 84 g as a result of reducing the numbers of nozzles from 5 to 4 and later 3 nozzles, respectively. A significant drop in the amount of scale removed by 78.5, 5.5 and 1.4 g across the NCN arrangement of 3, 4 and 5 nozzles configuration which further reduces by 13.8, 3.9 and 1.1 g, respectively as a result of shifting the atomizer head 50 mm and later 75 mm way from the scaled target (Figure 9b and c).

Throttling up the injection pressure to 10 MPa at 25 mm stand-off distance increased the average removal of all the respective header/nozzle configurations to 24.6, 21.2 and 18.1% as shown in Figure 10a. The study found the NCN configuration as the most effective in removing hollow shaped scale due to its ability to brake scale sample. This can be credited to absence of centre nozzle and therefore the jet strength is diverted to the side nozzles which are not just in good contact with scale sample but aided the hoops stress mechanism. Also, the NC and NCO were found less effective on this scale types as a result of the jet strength being diverted to the center nozzle, which sprays through the hollowness of scale making little or no contact with the target. An average scale removal difference of 0.6, 1.1 and 3.45% was also recorded between NCN and the other nozzle configuration for all the respective injection pressures. Further throttling the high-pressure water pump to 10 MPa at 25 mm distance impressively increases the paraffin removal capacity to 254, 77 and 58.3 g across the NCN arrangement and the respective nozzle configurations. A paraffin removal value of 58.3 g was initially achieved with 5 nozzles at 10 MPa at 25 mm stand-off distance which slightly improved by 18.3 g and subsequently by 195 g, as a result, altering the header configuration to 4 and later 3 nozzles, respectively. The
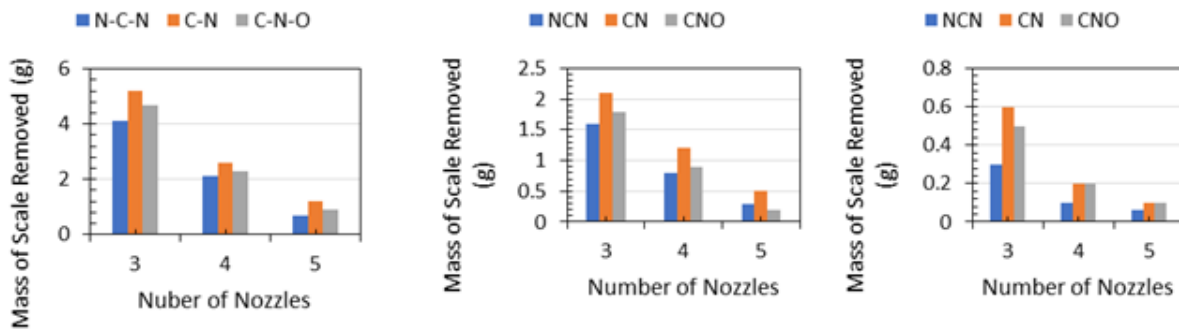
Figure 11. Solid paraffin deposit removal result at 4.8 MPa from (a) 25 mm, (b) 50 mm and (c) 75 mm distances.

(a) 25 mm stand-off distance   (b) 50 mm stand-off distance   (c) 75 mm stand-off distance
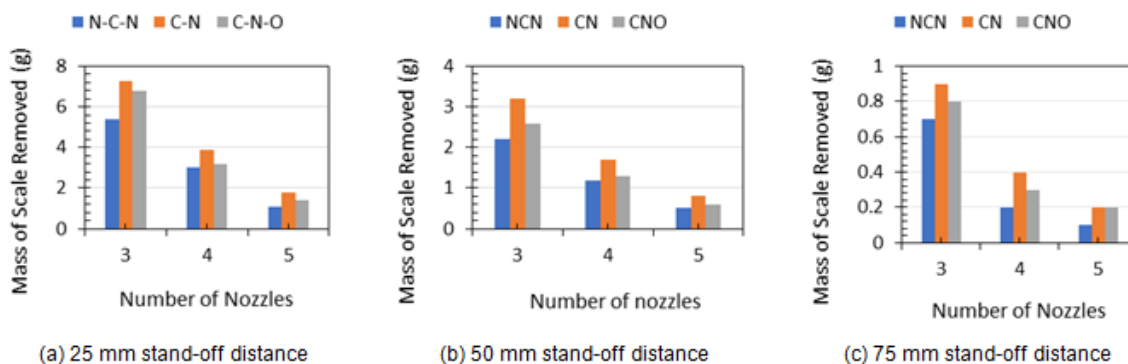
Figure 12. Solid paraffin deposit removal result at 6.0 MPa from (a) 25 mm, (b) 50 mm and (c) 75 mm distance.

10 MPa injection operation followed a similar trend with that of 4.8 and 6.0 MPa in terms of altering downstream distance by a paraffin removal free fall of 220, 54.8 and 48.5 g across the NCN arrangement of all the respective nozzle configuration as a result of pushing the jetting positions 25 mm away from the scaled target as shown in Figure 10b. Consequently, moving the atomizers header 25 mm further away from the target scale additionally reduces the effect of altering injection pressure and numbers of nozzles, at NCN arrangements, by 28, 21 and 9.6 g as elaborated in Figure 10c.

Figures 11 to 13 graphically demonstrate the quantitative impact of altering header configuration (in order words of numbers of nozzles and their arrangement), injection pressure and stand-off distance towards the amount of paraffin removed when descaling a complete tubing blockage scenario, that is, solid deposit. Similar removal trend to that of hollow scale deposit that linked the increase in scale removal with an increase in injection pressure, reduction in the number of nozzles and reduction in stand-off distance were observed. Though, the CN arrangement was found more effective than CNO and far more effective than NCN

arrangement due to the introduced center nozzle having more impact and direct contact with the scale surface target in addition to better scale particle lifting capacity and scale particle abrasion. The results of the entire solid deposit removal were found to be lower than the hollow scales removal results due to their 30 mm thickness differences.

Figure 11a qualitatively elaborates how the NCN, CN and CNO arrangement of 3, 4 and 5 nozzles configurations, at low injection pressure of 4.8 MPa and 25 mm distance, were averagely able to remove 0.2, 0.5 and 0.4% of the paraffin scale deposit. Although the low-pressure operation started by poorly removing 5.2, 2.6 and 1.2 g of paraffin deposit across the CN arrangement of the 3, 4 and 5 nozzle configurations at 25 mm distance. The initial 5 nozzle removal value of 1.2 g increased by 1.5 g and significantly by 4 g after subsequently reducing the numbers of nozzles to 4 and later 3 nozzles. Figure 10b and c shows how the removal capacity of the low pressure, CN arrangement of 3, 4 and 5 nozzle configuration caused a reduction of 3.1, 1.4 and 0.7 g, and less more by 1.5, 1 and 0.4 g after increasing the stand-off distance to 50 mm and later to 75 mm,
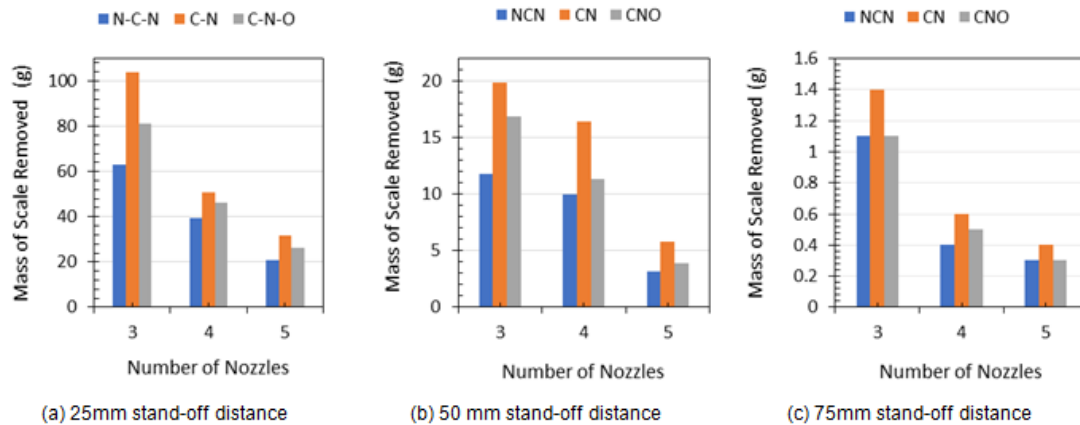
Figure 13. Solid paraffin deposit removal result at 10 MPa from (a) 25 mm, (b) 50 mm and (c) 75 mm Stand-off distance.

respectively.

Increasing the injection pressure from 4.8 to 6.0 MPa quantitatively increased the initial removal of the paraffin deposit by 0.2, 0.7 and 0.5% across the NCN, CN and CNO arrangement of the respective nozzle's configurations. While an increase in paraffin removal by 2.1, 1.3 and 0.6 g was also recorded from the 25 mm distance of the CN arrangements of 3, 4 and 5 nozzles configurations, respectively due to increasing the injection pressure to 6.0 MPa as graphically expressed in Figure 12a. The initial 1.8 g of paraffin deposit removed at the 6.0 MPa injection operation with the CN arrangements of 5 nozzles was doubled by 2.1 g and more significantly by 5.5 g as a result of reducing the header configuration to 4 and later 3 nozzles. Additionally, Figure 128b and c graphically expresses the decline in paraffin removal of the CN arrangement by 4.1, 2.1 and 1 g at 50 mm distance and 2.3, 1.3 and 0.6 g at 75 mm distance.

Finally, the analysis of further increasing the injection pressure to 10 MPa from 6.0 MPa in Figure 13a showed an averagely impressive scale removal increase by 6.6, 10.4 and 8.3%, respectively across NCN, CN and CNO of 3, 4 and 5 nozzles arrangement from 25 mm distance. This signifies an NC, CNO and NCN ranking order with CN being 0.3, 0.5, 3.8% more efficient than the rest of the nozzle arrangements at respective nozzle configurations and injection pressures. This can be attributed to good jet-surface contact of the center nozzle that aided both particles lifting capacity, particle abrasion and cyclic stress jetting mechanism. More importantly, the impressive removal values of 97, 47 and 30 g of paraffin across the CN arrangement of the respective header configurations recorded are due to increase in kinetic impact from the 4 MPa pressure increase. Similarly, the same operation substantially removed 32 g of paraffin by

utilizing 5 nozzles with the CN arrangement that increase by 19 g and skyrocketed to 72 g as a result of reducing the nozzle count to 4 and subsequently 3. A decrease in paraffin removal value of 4.1, 2.2 and 1 g across the CN arrangement of the respective nozzle configurations were recorded at the 50 mm distance operations that consequently further reduced by 2.3, 1.3 and 0.6 g as a result of increasing the stand-off distance to 75 mm.

Conclusion

(1) The experimental results irrespective of the shape of the deposit in question demonstrated a trend that connected the increases in the amount of scale removed to increase in injection rate (kinetic energy) and reduction in number of nozzles due to multiple nozzle pressure drop effect.
(2) Additionally, with reduction in downstream distance which can be compensated with the right choice of nozzle arrangement that depend on the shape of the scale deposit in question.
(3) For hollow shape scale, the triangle nozzle arrangement (or NCN) showed better efficiency in scale removal due to the shape of the scale and good contact between the side nozzles and the scale surface.
(4) For solid shape scale, the diagonal nozzle arrangement (or CN) showed better efficiency since there is also spray impact from the center nozzle as well as those on the side. Therefore, more scale could be removed compared to other nozzle arrangements.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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