# Empirical Analysis of Paraffin Scale Removal from Production Tubing with Multiple High-Pressure Water Jets


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# Declaration

I, Idoko Job John, declare that this dissertation report is my original work, and has not been submitted elsewhere for any award. Any section, part or phrasing that has been used or copied from other literature, or documents copied, has been referenced at the point of use as well as in the reference section if this dissertation.

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# Abstract

This work is an investigation into the suitability and feasibility of using multiple high-pressure (HP) water jets for the removal of soft scales from production tubings to discourage the use of corrosive chemicals and solid-entrained-liquids for the same purpose. While oil field scales cause flow assurance problems such as reducing the area of flow, pipe blockage, clogging of process facilities and consequent increase in operating cost due to workover operations, removing them with chemicals presents the hazard of contamination to surface water aquifers and the marine environment and solid particles have high abrasive potential and can erode pipe internal surfaces. Solids-entrained liquids are also heavier to pump and more problematic to rotating parts of machinery than pure water.

To carry out the study, 54 experimental trials were done to study the effect of four factors on the efficiency of scale removal with multiple flat-fan nozzles at an orientation of 25°. The variables investigated are the number of nozzles (3, 4 and 5), the spray injection pressure (4.8MPa, 6.0MPa and 10MPa), the spray distance or stand-off distance (25mm, 50mm and 75mm) and the condition of the production tubing which was either ambient (representing the in-situ tubing pressure) and compressed (in which case the effect of compressing the tubing on scale removal efficiency was studied by compressing the scale to 2bar through the injection of compressed air).

The experimental set up comprises of hollow soft scale samples, fabricated from household candles and tested for their representativeness of paraffin scales, which were inserted in a descaling rig comprising of a HP water pump, a control board for flow regulation and monitoring and a descaling chamber incorporated with a 16mm clear acrylic tube that models the production tubing and holds the scale samples and nozzle headers in place for the former to be sprayed.

The experimental findings showed direct proportionality between the amount of scale removed and spray injection rate, while the scale removal ability of the system reduced as the number of nozzles and spray distance increased. Furthermore, the mass of scale removed was higher when the scale was compressed due to the additional stress exerted by the compression and wave fluctuations around the scale sample. An additional 114.5g of scale was removed (over the mass removed at ambient tubing condition) with compressing the tubing, and hence, scale sample by 2bar and spraying at 6.0MPa injection pressure with 4 nozzles at 25mm stand-off distance. Also, multiple nozzles were observed to outperform single nozzles experimental trials under ambient tubing conditions and most cases under compressed tubing condition.

# CONFIDENTIALITY NOTICE

# Chapter 1: Introduction

## 1.1 Overview

The flow of crude oil and natural gas from subsurface petroleum and gas reservoirs to surface processing and storage facilities is driven by pressure difference and takes place usually along tubular conduits. One of such flow conduits is the Production tubing through which crude oil and natural gas are transported from the wellbore to the Wellhead. As this happens, variations in flow conditions such as pressure reduction, temperature drop, changes in flow diameter/cross-section, flow rates and flow across bends and elevations, etc., cause significant changes in the physical and chemical composition and the structure of the hydrocarbon. For waxy crudes, with low API, this change includes the precipitation of paraffin scales (or waxes) when the temperature drops below the wax formation temperature or cloud point of the hydrocarbon.

Paraffin scales present huge flow assurance challenges to the oil and gas industry. They can reduce the area available to flow (as in Figure 2.1) and create significant pressure drops and back pressures. Also, if unchecked, scale depositions can completely block flow conduits. Scales can form anywhere across the production conduit; from the reservoir to storage tanks. However, clogging of surface facilities by waxes are more common due to the reduced temperature.

Scale production prevention techniques currently include the use of chemical inhibitors and deliberate attempt to keep oil field facilities above the cloud point of the flow stream through direct heating and thermal insulation. When deposited, scale removal techniques or pigging include the use of chemical dissolvers, physical removal of the deposits with solids-infused high-pressure water, direct heating and some time, complete extraction of the affected section of the production tubing.

Many dissolvers are corrosive to low alloy carbon steel at downhole conditions (Wang et al., 2017), solids are abrasive and increase pipe corrosion and chemical treatment of water increases its hazardousness to the environment. The use of aerated, HP water sprays provides eco-friendly and cheaper means of removing scale deposits on production tubing. This approach also has the advantages of limited alteration or damage to the formation and limited adverse effects on the integrity of the completion.

## 1.2 Research Aim

This study aims to investigate the suitability of using multiple water jets for production tubing descaling in the oil and gas industry.

## 1.3 Research Objectives

The following objectives will guide the attainment of the above-mentioned aim of the experiment.

i. To fabricate physical models or samples of paraffin scales.
ii. To test fabricated scale samples representativeness of typical oil field scales by comparing their physical properties with established physical properties of paraffin scales.
iii. To investigate the suitability of using multiple water jets over the use of a single water jet for paraffin scale removal and analyse the effect of increasing the number of water jets on the amount of scale removed.
iv. To study the effect of an increased production tubing pressure (or air concentration) on the amount of scale removed.
v. To investigate the relationship between the distance of the water jets nozzles from the scale deposit (stand-off distance) and the amount of scale removed.
vi. To find out the effect of varying the pressure of the water jet on the efficiency of scale removed.

## 1.4 Significance of the Study

This work provides insights into the factors that affect descaling of production tubing, that has been partially blocked by paraffin waxes/scales, with the use of multiple High Pressure (HP) water jets. It, therefore, offers a tool for quick decision-making regarding optimization of oil field descaling operations without the use of corrosive chemicals and solids-mixed water; thereby, reducing the environmental impact and cost of oil field scale removal operations.

## 1.5 Project scope

This study is limited to the removal of only hollow paraffin scales (soft scales) with water at high pressures. No attempt was made at improving the scale removal efficiency of the water through chemical treatment or the addition of solids.

# Chapter 2: Literature Review

## 2.1 Scale Formation in Petroleum Production

### 2.1.1 Overview

Surface production and transportation of petroleum from subsurface reservoirs to end-users are accomplished with pipelines (Mansoori et al, 2017; Nejad & Karimi, 2017) such as the Production tubing, among other equipment and machinery or process vessels. These flow conduits, sometimes, suffer flow restrictions due to solids depositions and corrosion failures due to internal abrasion by suspended solid particles (Peng & Guo, 2017). These solids, which constitute flow assurance problems, include natural gas hydrates, waxes, asphaltenes, naphthenates, scales and emulsions (Borden, 2015; Theyab, 2017).

According to (Amjad & Koutsoukos, 2010), mineral scales which cause flow restriction concerns in the oil and gas industry include "calcium carbonate, calcium and barium sulfates, magnesium-based scales, silica scales, iron scales, calcium phosphate, and struvite". In addition to these, wax scales which are common in highly paraffinic hydrocarbons have been termed as "soft scales" by (Abbas, 2014) and (Abbas et al., 2016).

The location of scale deposition is a function of the nature of the scale and the compositions of the fluid. In the reservoir, they block reservoir pores and cause formation damages. In pipelines and surface facilities, they cause severe operational problems (Moghadasi, et al., 2003).

In the following sections,  scale production in oil and gas wells is studied further with emphasis on their classification, formation, prevention and remediation.

### 2.1.2 Description and Classification of Scales associated with Petroleum Production

Oil and gas production associated scales can be grouped into organic scales and inorganic scales. While paraffin and asphaltic materials are examples of the former (Braun & Boles, 2007), inorganic scales can be further classified into carbonate and sulphate scales (Vazirian, 2015).

#### 2.1.2.1 Organic Scales

Organic deposits, that are formed during oil and gas production, have led to high lifting costs, equipment wear and corrosion, flow restrictions, decreased production and consequent overall return on investment (Anwar & Abubakr, 2017; Braun & Boles, 2007; Brown & Dobbs, 1998; Elmorsey, 2013; Gupta et al., 2009; Ramones et al., 2015).

Figure 2.1 shows two cases of organic scale depositions in oil well production tubing.

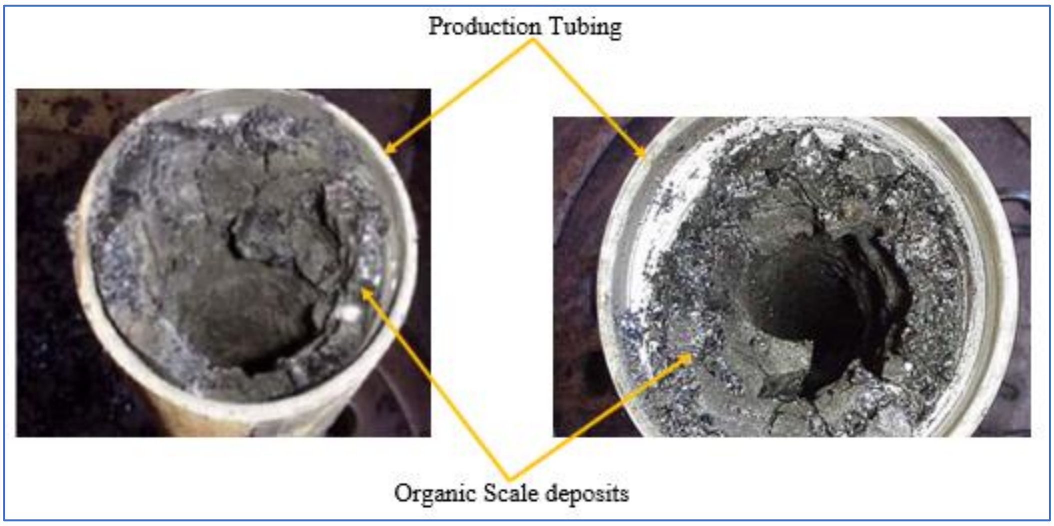



Figure 2.1: Produced crude flow area reduction by deposits of asphaltene (left) (Mullins, 2005) and paraffin (right) (ENVIROFLUID, 2014).

Organic scales are heavy, low solubility hydrocarbons that are, however, sludge-forming in acid solvents and are mostly paraffins and asphaltenes formed by precipitation from produced crude due to pressure and temperature reductions along production conduits (Fulford, 1975; Moghadasi et al., 2003; Ramones et al., 2015; Vazirian et al., 2015). They are, therefore, mostly associated with fields that produce heavy crudes which are globally distributed as shown in Figure 2.2 (RIGZONE, n.d.).

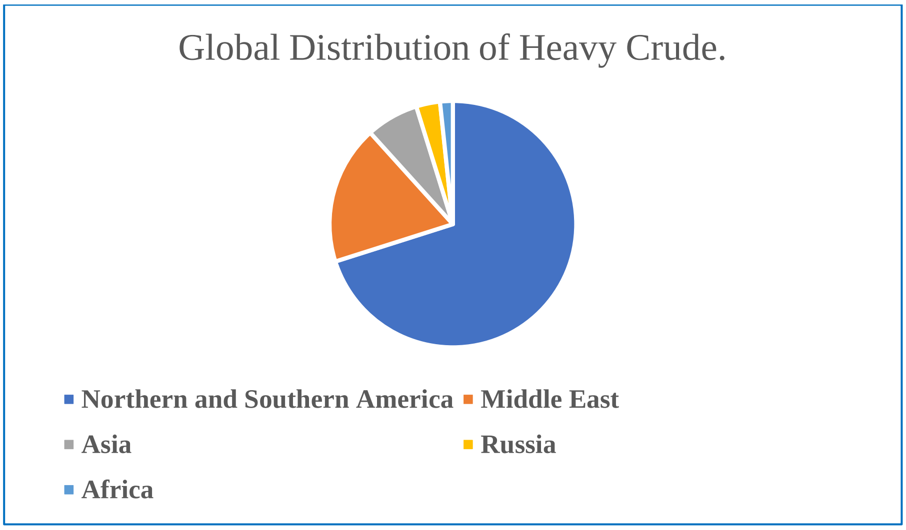



Figure 2.2: Global Distribution of Heavy Crude (RIGZONE, n.d.).

### i. Paraffinic Scales

Depending on the chemical composition of the source of the hydrocarbon, the associated organic scales can be, either, paraffinic or asphaltic, or a combination of both. Paraffin are long-chained saturated hydrocarbons of the alkane family. According to (Brown & Dobbs, 1998), paraffin has over 18 carbon atoms in length and the chains may be linear or branched.

(Thomas, 1988) defines Paraffins as hydrocarbons "containing carbon numbers ranging from 18 to greater than 60, and is for the most part, linear". They are also insoluble in the crude at the producing temperature and pressure and are made up of both straight and branched-chain aliphatic hydrocarbons, aromatic hydrocarbons, naphthenes, resins and asphaltenes (Sanjay et al., 2007).

#### ii. Asphaltic Scales

Asphaltic and paraffinic scale problems can exist in the same well (Gupta et al., 2009).

Asphaltenes are usually defined by their solubility behaviours. They are also a complex mixture of compounds that are dissolved in crude oil, at conditions that favour their solubility in oil, and they are commonly defined as being soluble in toluene and insoluble in n-heptane. Besides scale production, asphaltenes also reduce the value and quality of refined petroleum products (especially, transportation fuels) due to their hydrogen deficiency (Mullins, 2005).

### 2.1.2.2 Organic Scale Deposition Mechanism

From the foregoing description of asphaltic and paraffinic scales, it can be deduced that organic scales are inherent components of petroleum that are in solution with the hydrocarbon at conditions that favour their solubility. Therefore, they come out of solution (or they are precipitated) when the oil can no longer hold them in solution. In other words, at some point in the reservoir, along production conduits in the well, pipelines or process facilities at the surface, the paraffin or asphaltic content of the produced crude exceeds it solubility and form clusters which attach themselves to the walls of the conduit, process if the lifting or driving force is not enough to produce them or keep them flowing. Organic scale precipitation is caused by temperature changes and the evolution of gases and lighter products as crude oil is being produced or transported (Sutton, 2007).

Organic scale deposits can be either predominantly paraffinic wax or entirely asphaltic. (McClaflin & Whitfill, 2007) posits that "most deposits, however, fall between these two extremes and comprise a mixture of asphaltic material, solid hydrocarbon waxes, and various amounts of retained oil, water, sand, silt, metal oxides, sulfates, and carbonates".

#### iii. Paraffinic Scales Formation Mechanism

Temperature plays a crucial role in the formation of paraffin scales (Sanjay et al., 2007), especially in pipelines used for oil transport. (Turbakov & Riabokon, 2014) explains that there is no consistency in the formation pattern along the pipeline; noting that the deposition is negligible at the upstream region of the pipeline, which is characterised by temperatures above the paraffin crystallization temperature (or cloud point of the oil). But afterwards, paraffin is released, and its deposition grows as temperatures become lower downstream of the inlet. After this stage, the rate of deposition and consequent thickness of paraffin begins to decrease because the flow of oil is almost isothermal – a condition which does not favour further deposition of the paraffin. The highest paraffin formation occurs where the temperature is least and oil cooling, along the pipeline, is highest. This is during any downtime period. Freezing increases from the middle of the wall of the pipeline and propagates towards its centre, such that the stream in the centre of the pipeline becomes more mobile than those at the walls which are more susceptible to being left attached to the pipeline when pumping resumes.

Paraffin formation mechanism is summarised into the four stages shown in Figure 2.3 by (Thomas, 1988).

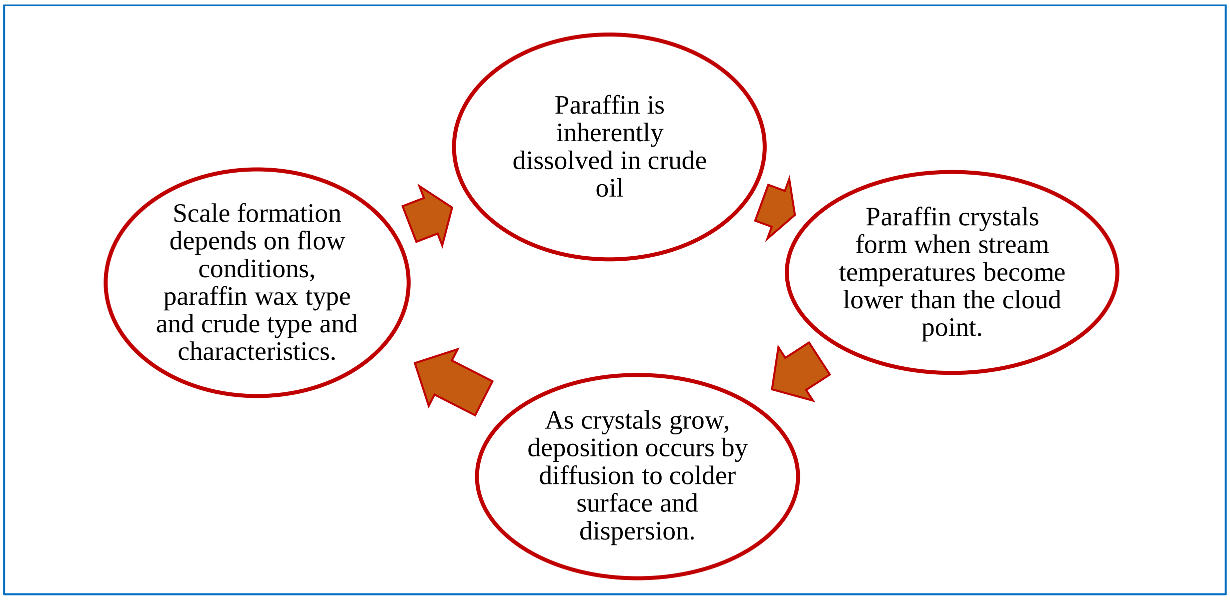



Figure 2.3: Paraffin Scales Deposition Mechanism (Thomas, 1988).

**iv. Asphaltic Scales Formation Mechanism.**

Asphaltene formation from live, highly compressible, undersaturated crude has been associated with pressure drop (Mullins, 2005). Like paraffin formation, asphalts also form by precipitation and the process is highly influenced by well turbulence and the nature of the substratum (Boer et al., 1995).

#### 2.1.2.3 Inorganic Scales

As earlier mentioned, the two major types of inorganic scales, commonly found during oil and gas production, are carbonate scales such as Calcium Carbonate ($CaCO_3$) and Iron (II) Carbonate or Ferrous Carbonate ($FeCO_3$); and Sulphate scales which include Barium Sulphate

($BaSO_4$), Strontium Sulphate ($SrSO_4$) and Calcium Sulphate ($CaSO_4$) (Moghadasi, 2003; Moghadasi, 2003; Vazirian, 2015).

#### 2.1.2.4 Inorganic Scales Deposition Mechanism

The parent minerals or elements in the above-mentioned inorganic scales are present in saltwater which is initially and always present in petroleum and gas reservoirs. Changing flow conditions and the flow environment cause their liberation from solution as crude oil is being produced.

Scale deposition process has, however, been broadly classified by (Vazirian et al., 2015) into (1) Deposition and (2) Adhesion; the Deposition stage describes the period of nucleation and adhesion to surfaces rough enough and at conditions suitable for the process while the Adhesion phase describes the aggregation of existing crystals and consequent scale build-up.

According to (Moghadasi, et al., 2003), carbonate scale formation is attributable to pressure and PH changes of the production fluid while sulphate scales form when incompatible brine from formation water or injection water combine. The authors noted that the conventional use of seawater for pressure maintenance and primary recovery connotes that calcium and strontium scales issues are likely to be encountered during the production life of a field. To buttress this, they gave an instance of the Iranian offshore Siri field where scale formation led to a rapid decrease in injectivity and eventual stoppage of a water pressure maintenance operation.

Explaining the chemistry behind scale formation from mixtures of incompatible water sources, (Aregbe, 2016) gave an instance of seawater and formation water mixing. Stating that the former is high in sulphate ions and formation water has high calcium, barium and strontium ions; such that a mixture of them could lead to the precipitation of calcium sulphate, barium sulphate and/or strontium sulphate hard scales. The case of calcium sulphate is shown below.

$$Ca^{2+} + {SO_4}^{2-} \leftrightarrow CaSO_4$$

### 2.1.3 Oil Field Scale Prevention and Removal Approaches

#### 2.1.3.1 Preventive approaches.

Several authors have reported the methods that the oil and gas industry currently employ in preventing scale formation. Others have also narrated remedial options that are utilized after scales have formed. The following three methods have been reported.

**i. Chemical Inhibition**

Paraffin scales formation has been mitigated, even at cold temperatures, with chemicals which alter the flow properties of waxy crude oil. One of the earlier reporters of this is (Fulford, 1975) who determined the effectiveness of commercial paraffin prevention chemicals by performing an empirical investigation of factors that influence paraffin deposition with an apparatus built to measure the pressure and variations in the rate of flow that was caused when paraffin formed from crude oil in a 1.5inch diameter steel pipe. Since only paraffin was investigated in this work, more can be done by testing the efficacy of the same and similar chemicals on other oil field scales, especially asphaltenes.

#### ii. Dilution

Scale prevention through chemical inhibition has also been recognised by (Crabtree et al., 1999), who also reported two means of doing that, as the most effective way of fighting scale. Dilution – one of the two techniques earlier mentioned – is commonly used in high-salinity wells to control halite precipitation by ensuring a continuous supply of freshwater to the sandface through macaroni strings as shown in Figure 2.4. The second inhibition approach involves the use of chemical inhibitors, earlier mentioned, which work by either chelation or scale-nucleus-growth mitigation.

#### iii. Surface Coating

Besides chemical inhibition, Vazirian et al., (2015) mention that scale formation can also be reduced by altering the properties of the surfaces on which scale deposition is likely to occur or by simply coating such surfaces. The authors explain that when using this approach, important parameters to consider include: pipe roughness, pipe wettability, crystallization kinetics, surface deposition kinetics, induction time for surface scaling, flow regime and flow characteristics.

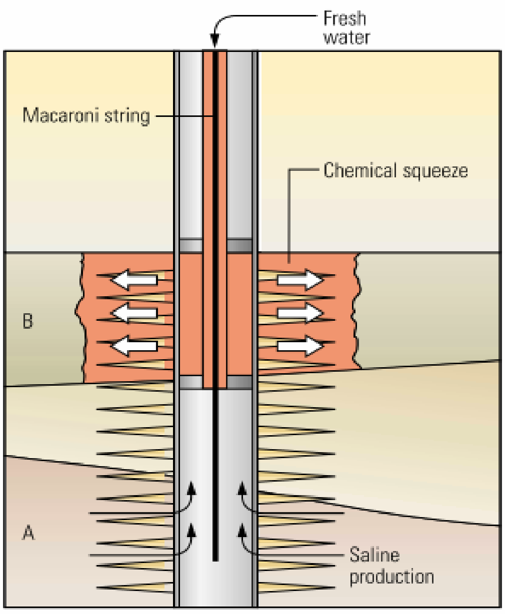



Figure 2.4: Macaroni string showing chemical delivery to scale-prone interval A and a periodic inhibitor squeeze into B (Crabtree et al., 1999).

#### 2.1.3.2 Removal Approaches

Once formed and deposited, scale removal becomes crucial to avoid its menaces. While dissolvers are available for dissolving some, others such as calcium sulfate have been reported to be very hard and may not be easily dissolved by known dissolvers.

**i. Production String Replacement**

Scale formation tendency can be foreseen with the use of compatibility tests, petrographic techniques and quantitative calculations using specific software (Hamdy et al., 2014). Such prediction will save operators the cost of a total replacement of an affected string which is the solution as the scale build-up reduces production, continuously, until a rig has to be mobilized to replace the production string (Guimaraes et al., 2008).

**ii. Chemical Dissolvers**

Narrating the "development and field application of chemical treatment to remove scale in an offshore 8" production line in Gemsa oil field", Elmorsey (2013) described a successful descaling of a calcium sulfate deposit with the use of a specially formulated chemical dissolver. The operation was said to involve three processes: (i) pre-flushing with an organic solvent; (ii) the main treatment with the chemical dissolver and; (iii) post-flushing with injection water.

A similar laboratory design of a suitable chemical for the descaling of a production well in the Belayim land field (Sidri formation) was reported published by (Hamdy et al., 2014).

In the two cases presented above, the descaling programmes were designed taking into consideration the nature of the scale.

**iii. Spraying with High Pressure (HP) Water Jets**

Mechanical removal of deposited scales with high-pressure water sprays have been studied by a few authors who have also made efforts to improve the process. This is because water is cheaper than chemicals. The latter also possess the threat of environmental pollution.

Recognizing that the use of solid particles in combination with HP water sprays in the descaling operations causes safety and environmental challenges, (Abbas, 2014) admonishes the use of only high pressure aerated water sprays at high impact force. Admitting the deficiency of this technique due to the reduction in cavitation bubbles along the production tubing when high-pressure water sprays are applied, the author demonstrated that the application of air-water combination, termed aerated sprays, presents a better alternative to scale removal from production tubing without the use of solid particle or cavitation bubbles in the HP water jets.

In a similar investigation, (Enyi et al., 2012) proposed the use of overlapping flat fan atomisers to generate water jets at $23\ l/min$ that will make an impact with scale deposits at $0.657 MPa$ and remove such solids along the production tubing. The distribution of the impact pressure in such atomizer was later investigated by (Abbas et al., 2016).

#### iv. Rigless intervention

The above three scale removal methods involve the use of either workover rigs or coiled tubing or macaroni strings. Oil field descaling operation without the hassle and expenses of a rig has been advised by (Guimaraes et al., 2008), who detailed the planning, logistics and execution of a rigless scale removal operation which helped to increase oil and gas production from two fields located offshore Brazil; both fields suffering severe scale depositions – barium sulfate in the oil field and calcium carbonate in the gas field.

## 2.2 Research and Development Studies into Oil Field Descaling

Both numerical and empirical research have been extensively conducted about oil field descaling. A combination of computer simulation of numerical models and laboratory studies of physical models have been employed as well; (Franco et al., 2010) used sophisticated computer packages to carry out a detailed analysis of laboratory studies outcomes, well production history, reservoir geology, static and dynamic properties and reservoir description to identify and forecast the different types of mineral scales and the formation damage mechanisms that are prevalent or likely to occur in the reservoir and the wellbore under different reservoir and producing conditions. The results of the work are then used to design future scale prevention and remediation programs for the field (a rich gas condensate field).

Unlike the use of numerical models or computer simulations as employed by (Franco et al, 2010), (Khormali & Petrakov, 2016) conducted a laboratory investigation of a new inhibitor, specifically, of calcium carbonate scales, in oil reservoirs and production equipment. The Performance indicators employed by the authors in the assessment of the new inhibitor are scale inhibition efficiency, the optical density of the solution, induction time of the scale formation, corrosion activity and adsorption-desorption abilities of the inhibitor.

As earlier mentioned, scale formation is also affected by flow conditions, among other factors. Paraffin deposition, posited to be predominantly influenced by temperature changes, was studied under single-phase turbulent flow conditions by (Mirazizi et al., 2012) who examined the behaviour of various parameters including deposit thickness, wax content, and deposit wax mass under different flow characteristics such as wall shear stress, Reynolds number, and radial temperature gradient. The authors revealed that turbulence, as well as radial temperature change significantly affects paraffin scale deposition.

In another report of successful use of chemical inhibitors for scale removal, (Nasr-El-Din, Al-Gamber, & Saiari, 2006) designed a chemical inhibitor for horizontal wells prone to calcium carbonate scale deposition, in a sandstone reservoir, following an acid cleanout of earlier depositions. Once treated wells continued production, fluid sampling was done and well flow back samples were monitored, tested and examined to determine the effect of the treatment on reservoir integrity, produced fluid contents and to determine the Minimum Inhibitor Concentration (MIC) and to confirm if the emulsified scale inhibitor dissociates in the formation as expected.

Iron sulphide scales present unique, significant challenges in sour gas wells (Wang et al., 2018; Denney, 2015; Chen et al., 2018; Wang et al., 2017; Al-Dossary et al., 2014). Several operations involving this scenario have been published from gas fields globally and studies have also been done to mitigate it. Among such publications is (Wang et al., 2016) in which scale composition was analysed for a large number of scale samples collected during well workover and interventions. The study provides important information for the understanding of scale formation process, scale constituents and oil field scale chemistry.

In a review of advancements and highlight of the challenges of its management in sour gas production systems, (Chen et al., 2019) covered the formation mechanism, removal techniques and the prevention strategies of iron sulphide scales and summarised cutting edge technologies and developments in mechanical and chemical methods of removing downhole tubing deposits of iron sulphide scales. The study revealed that the production tubing can also be a source of the constituents of oil field mineral scales, noting that the iron released from the tubing due to corrosion during production and acidizing treatments are sources of iron sulphide deposition in near-wellbore region, downhole tubing and surface facilities.

Integration of field performance, formation water geochemical analysis and experimental studies have been used by (Al-Arji & Al-Amri, 2013) to identify scaling tendencies and predict future scaling issues when formation and injected water incompatibilities created scale deposition challenges during a pressure maintenance programme. Full recovery of well performance after treatment with $15\ wt.\%$ HCl, successful retrieval of stuck SCSSV (Surface Controlled Subsurface Safety Valve), mapping of scale build-up locations through production data analysis and calcium carbonate scale formation prediction through Scaling Index (SI) tests were reported as outcomes of the study.

The possibility of using non-corrosive, non-HCl based descaling chemicals was tested by (Anwar & Abubakr, 2017) who studied the use of a novel, non-corrosive descaling agent in removing calcium carbonate and iron scale deposits from near-wellbore regions. To do this, downhole samples of the deposits were collected and studied empirically to determine their dissolution effectiveness. Furthermore, the effect of the proposed removal agent on the formation (sandstone) minerals and the corrosion properties of the chemical on carbon steel tubular in the presence of hydrogen sulphide were examined. The study showed that 80% of scale deposit can be removed, after twelve hours of soaking with the new chemical agent, without adverse effects on the reservoir or completion.

In similar research, (Chen, et al., 2017) reported how the use of a specially formulated, non-acidic dissolver was successfully to remove iron sulphide from downhole completions. The key performance indicator (KPI) of such alternative dissolvers are (i) high ability to dissolve the scale; (ii) low corrosion to carbon steel; (iii) no $H_2S$ production and (iv) no formation damage. The experiment was conducted through static dissolution test and the performance of the new dissolver was compared with three HCl based dissolvers. To examine the corrosive tendency of the new agent, generalized and localized corrosion tests were carried out at elevated temperatures while the effect of the chemical on formation properties and reservoir stimulation were studied using dynamic core flooding and x-ray computerized tomography (CT) scanning. The results of the experiment showed that the new dissolver was more efficient in iron sulphide removal and of less corrosive and formation damage effects relative to the acid-based agents.

### 2.2.1 Research loopholes and Limitations

Table 2.1. summarizes some notable studies into oil field descaling. An attempt is also made to identify research loopholes in the studies that can be exploited to further improve scale mitigation and removal operations in the oil and gas industry.

TABLE 2.1: SUMMARY OF PREVIOUS R&D STUDIES ON INDUSTRY SCALE PREVENTION AND REMOVAL APPROACHES

| S/N | CITATION AND TITLE OF PUBLICATION | SUMMARY OF WORK | LIMITATION(S), RESEARCH GAPS, REMARKS |
|---|---|---|---|
| 1. | Fulford, R. S. (1975). Oilwell Paraffin Prevention Chemicals. | An experimental analysis of the viability and strength of different chemicals that are used to prevent paraffin formation. | The scope of the study was limited to paraffin scales. That leaves room for investigations into the effectiveness of the same and other chemicals for |

| S/N | CITATION AND TITLE OF PUBLICATION | SUMMARY OF WORK | LIMITATION(S), RESEARCH GAPS, REMARKS |
|---|---|---|---|
| | | | asphaltene and hard scales prevention. |
| 2. | Abbas, A. J. (2014). Descaling of Petroleum Production Tubing utilizing Aerated High-Pressure Flat Fan Water Sprays. | An investigation into the prospect of utilizing HP aerated water spray for production tubing descaling of solids or bubble cavities in the HP water jets. | The experiment was performed with a single jet of water or a single nozzle head. A rotary nozzle or/and the use of multiple nozzles may provide a greater surface area of contact between the sprays and the scales. |
| 3. | Franco, C. A., et al., (2010). Analysis of Deposition Mechanism of Mineral Scales Precipitating in the Sandface and Production Strings of Gas-Condensate Wells. | A description and forecast of scaling and formation damage issues of a gas field through extensive analysis of reservoir history, geology and characteristics; well and field operating data. | The study is built on basic principles such as material balance and therefore, subject to errors associated with the latter which are usually due to the numerous assumptions inherent in generating them. Also, the finding may not apply to green fields if the data for the studies were gotten from mature fields and vice-versa. |
| 4. | Khormali, A., & Petrakov, D. G. (2016). Laboratory investigation of a new scale inhibitor for preventing calcium carbonate precipitation in oil reservoirs and production equipment | Formulation of a new chemical inhibitor for calcium carbonate scale formation prevention. | The optimum mass percentage of the inhibitor is 8% to 10% of 5% HCl which is expensive and will lead to higher operating expenditures. |
| 5. | Mirazizi, H. K., et al, (2012). Experimental investigation of paraffin deposition under turbulent flow conditions. | Laboratory analysis of paraffin formation when the flow is turbulent. | Ceteris paribus, the wax deposition should be higher under laminar flow conditions. The study did not consider this flow regime. |
| 6. | Nasr-El-Din, et al., (2006). Field Application of Emulsified Scale Inhibitor Treatment to Mitigate | A narrative of the design and application of an emulsified scale inhibitor squeeze | The use of chemical inhibitors presents the challenges of environmental hazards and extra |

| S/N | CITATION AND TITLE OF PUBLICATION | SUMMARY OF WORK | LIMITATION(S), RESEARCH GAPS, REMARKS |
|---|---|---|---|
| | Calcium Carbonate Scale in Horizontal Wells. | treatment and the analysis of produced fluids. | cost of treatment of produced fluid. |
| 7. | Chen, T et al., (2019). Recent Development and Remaining Challenges of Iron Sulphide Scale Mitigation in Sour Gas Wells | A review of industry approaches to iron sulphide scale management that also provides comprehensive explanations into its formation mechanism. | This work also highlighted research loopholes and technical gaps that can be further exploited to improve iron sulphide scale management in the oil and gas industry. |
| 8. | Al-Arji & Al-Amri, (2013). New Workflow for Scale Precipitation in Production Equipment Resulting from Formation and Injected Water Incompatibility: Field Case. | The use of experimental and field performance studies in scale formation prediction and report of successful chemical treatment. | This study also advocates the use of HCl and acid treatment which are expensive, corrosive and environmentally unfriendly due to top $H_2S$ production. |
| 9. | Anwar, M., & Abubakr, M. (2017). Innovation Technique and Successful Scale Removal Job with Coiled Tubing in Belayim Oil Field, Egypt: A Case History. | A study on the use of unique, non-corrosive calcium carbonate and iron scale dissolver | Proposed chemical dissolver could still be harmful to surface water habitats. Its effect on the marine environment was not assessed. |
| 10. | Chen, T., Wang, Q., Chang, F., & Albelharith, E. (2017). Multi-Functional and Non-Acidic Iron Sulphide Scale Dissolver for Downhole Applications. | A study on the use of a new iron sulphide scale dissolver for downhole completions. | Proposed chemical dissolver could still be harmful to surface water habitats. Its effect on the marine environment was not assessed. |

# Chapter 3: RESEARCH METHODOLOGY

## 3.1 Introduction

The stages involved in this study can be summarised into three, namely: (i) fabrication of soft scale (wax) samples; (ii) testing of samples representativeness of oil field waxes and; (iii) descaling experiments. The experiment is further classified into scale removal at ambient chamber condition and scale removal at compressed chamber condition. In Figure 3.1, the steps in the experimental methodology are presented at a glance.

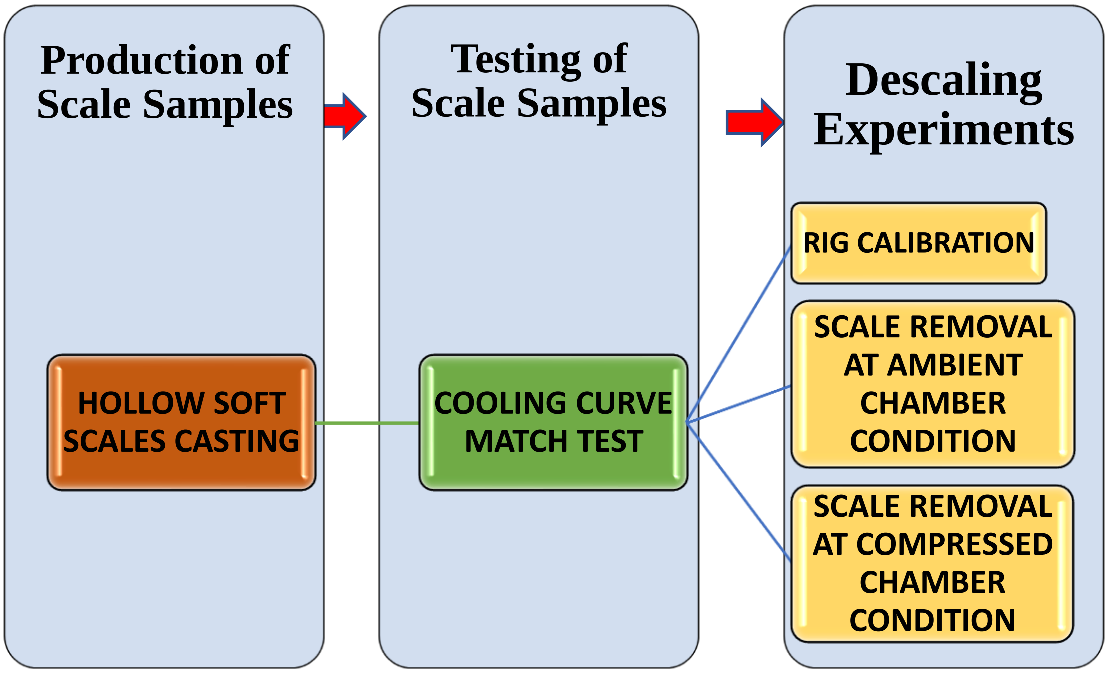



Figure 3.1: Research Methodology Tree at a Glance

## 3.2 Construction of Scale Samples

### 3.2.1 Materials and Apparatuses

All hollow soft scale samples used in this study were cast from household candles and tested for their representativeness of actual oil field paraffin waxes. In other words, the material for the experiment is household candles.

The Apparatuses for this stage of the experiment are:

(i) Safety knife
(ii) Baking pan
(iii) Oven
(iv) Mould
(v) Hack saw

(vi) Kitchen Rolls
(vii) Weighing balance

**The Mould**

The mould, made of high thermal resistant thermoplastic materials, has two concentric parts, and when assembled as shown Figure 3.2 has a height of 15cm, Internal Diameter, ID of 13cm and Outer Diameter, OD of 15cm. It has a melting point that is far above the temperature of the molten wax.

### 3.2.2 Hollow Soft Scales Casting Procedure

Figure 3.2 summarizes the scale casting process into (i) candle prepping; (ii) candle melting; (iii) molten wax pouring and setting; (iv) wax cutting and labelling

**i. Candle Prepping**

This stage entails preparing the household candles for casting. To do this;

a) The household candles were broken into smaller pieces with the safety knife.
b) Impurities such as candle threads and base plates were detached from the broken candles.
c) The candle pieces were then placed in the baking pan.

**ii. Candle Melting**

After breaking and removing non-waxy materials (impurities) from the candles;

d) The pan of candles was placed in the Oven
e) The oven was set at 100°C and heated for an average of 45minutes.

**iii. Molten Wax Pouring and Setting**

After melting;

f) The molten wax is carefully poured into the mould, decanted in the process so that any impurities, still left in it, settle at the base of the baking pan.
g) The wax is then allowed to cool and set. Average setting time of 100minutes was recorded.

**iv. Wax cutting and labelling**

Each mould was refined to generate two soft hollow scale samples. To do this;

h) The solid wax sample was cut into two halves, each of length 7cm.
i) A 1cm rough edge was cut off the top half.
j) Debris was wiped off both waxes with the kitchen rolls

k) Both waxes were then labelled and stored for usage.

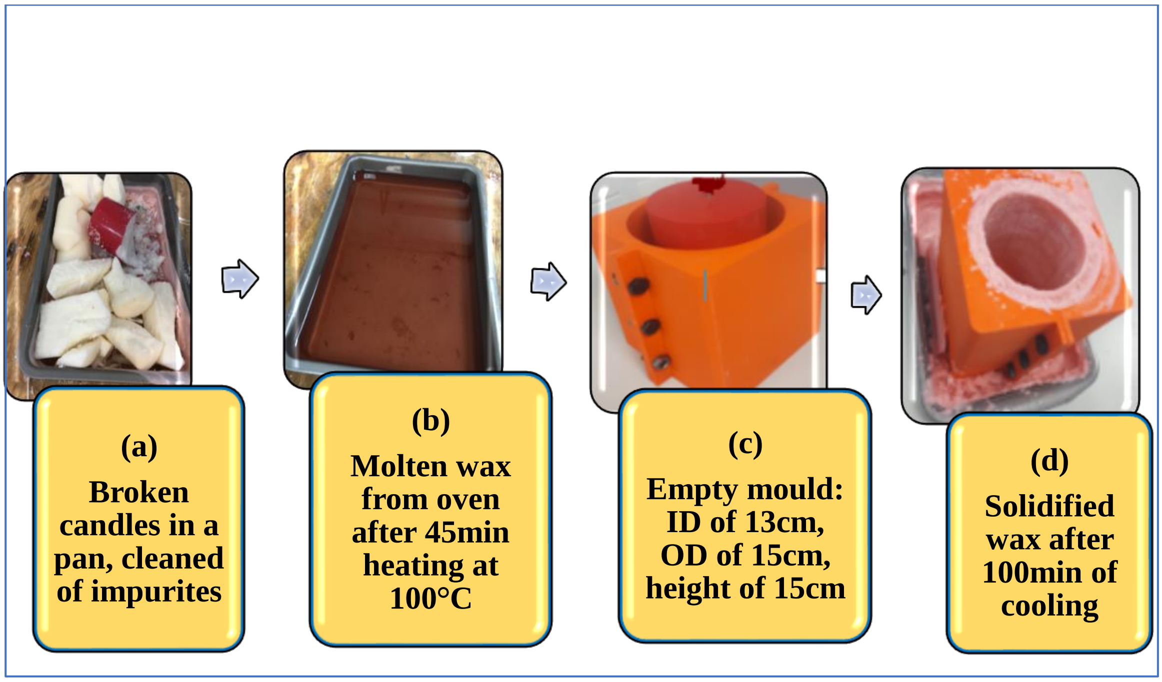



Figure 3.2: Hollow Soft Scales Fabrication Process

## 3.3 Testing of Scale Samples

To ensure that the fabricated scale samples are good representatives of typical oil field paraffin scales, the test described below was carried out on the molten waxes.

### 3.3.1 Materials and Apparatus

1. Molten Wax
2. Long Probe Waterproof Digital Thermometer

### 3.3.2 Procedure For Cooling Curve Match Test

This test involves obtaining the cooling curve for the wax samples and matching it with established and published cooling curves of typical oil field paraffin waxes; and, comparing its freezing point with oil field paraffin waxes. The steps taken to do this are:

1. More than three-fourths of the thermometer probe was inserted into the molten wax and the device is switched on.
2. The thermometer is held steady in the above position until temperature readings stabilized.
3. The temperature at that stage is taken and recorded.
4. The above three steps are repeated at two minutes intervals until the wax solidifies.
5. A cooling curve is generated from a linear plot of Temperature (°C) versus Time (min.).

6. The cooling curve of the wax sample is compared qualitatively (pattern match test) and quantitatively (Freezing point test) with published the paraffin cooling curves of (EDGE, 2013; Hasan et al, 2016).

## 3.4 Scale Removal (or Descaling) Experiment

Scale samples that pass the cooling curve test described in Section 3.3.2 are used in the descaling experiment proper. The experiment was conducted in two stages: (i) at ambient chamber condition and (ii) at compressed chamber condition.

### 3.4.3 Materials and Experimental Set-Up.

The materials used in the descaling experiment are fabricated and tested hollow soft scale samples (Section 3.2 and Section 3.2). The experimental set up includes:

1. Hollow Soft Scale Samples
2. Descaling rig
3. Weighing Balance
4. Timer
5. High-Resolution Camera

#### 3.4.3.1 Equipment Description

The weighing balance was used to obtain the masses of the scales before and after the experiments. The timer was used to control the duration of spraying while the camera was used for qualitative results taken or simply for taking snapshots of the scale samples before and after the experiments for qualitative analysis.

**1. Hollow Soft Scale Samples.**

The scale samples, shown in Figure 3.3 were fabricated and processed as described in Section 3.2 and Section 3.3. They are 7cm high and 2cm thick. The scale label, ID or reference 51SH refers to the $51^{st}$ Soft Hollow Scale for use under ambient chamber condition while 51SHA refers to the $51^{st}$ Soft Hollow Scale for use under compressed chamber condition.

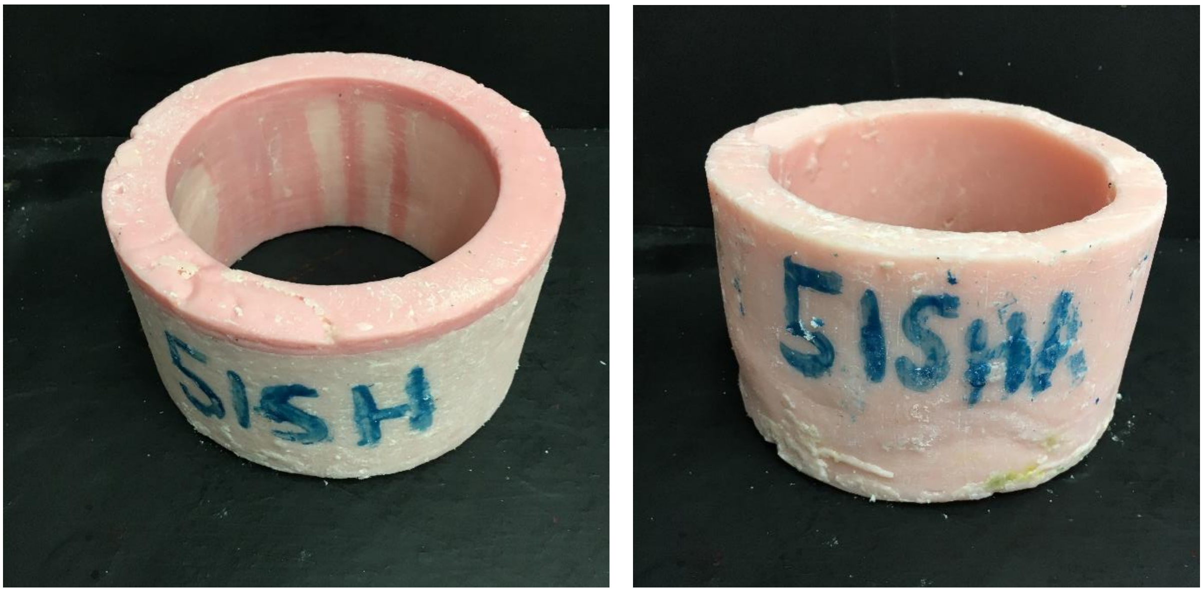


Figure 3.3: Samples of Fabricated Hollow Paraffin (Soft) Scales

**2. The Descaling Rig**

While the items of the Experimental set up listed in Section 3.4.1 are common to both stages of the experiment (descaling at ambient chamber condition and descaling at compressed chamber condition), the Descaling rig design and components vary for both stages of the experiment. The general components of the rig, common to both experiments are described in this section while the variations are highlighted in subsequent sections where the experimental procedure for each experiment is discussed.

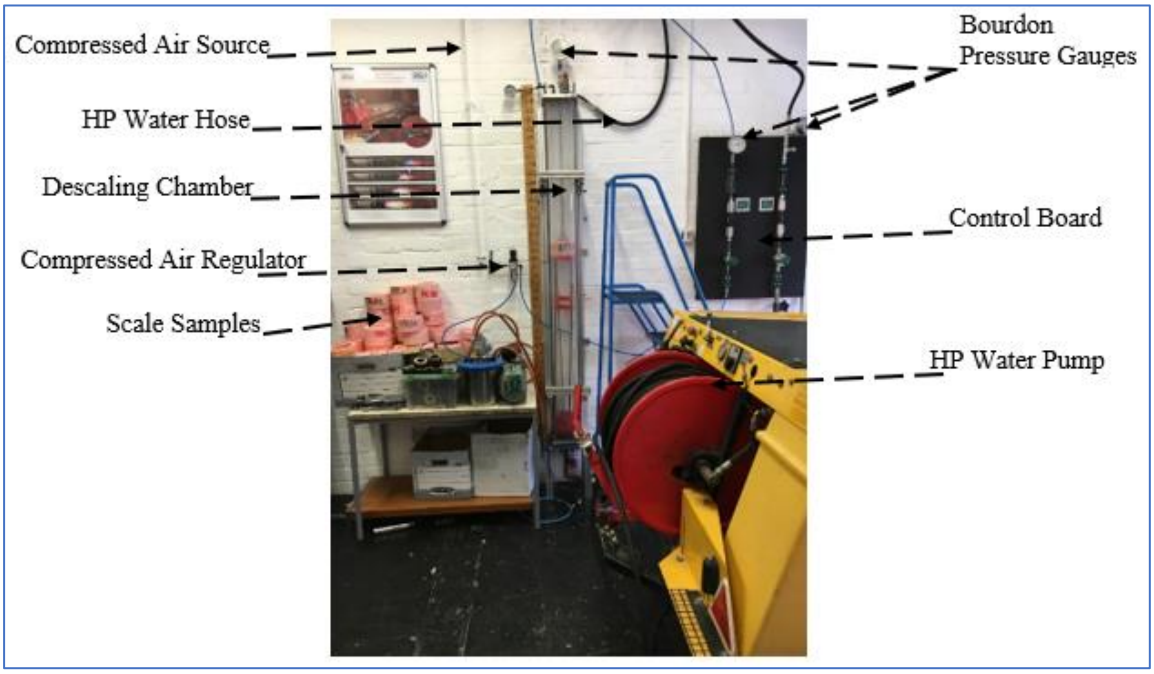


Figure 3.4: Complete descaling Rig Set-Up

The complete rig set up, Figure 3.4 comprises of three main parts namely (i) descaling chamber (ii) control board and (iii) high-pressure water pump.

### 3. The Descaling Chamber

The descaling chamber consists of a chamber header assembly, scale holder and bottom plate designed to create an airtight column in a clear acrylic tube and hold a scale sample in place for spraying as shown in Figure 3.5. The Chamber header, which hangs the nozzle header, is fitted with a 4bar pressure relief valve and a return inlet that can serve for both compressed air supply and chamber suctioning. The Bottom plate consists of a water outlet and while the multiple nozzle spray header utilized has 7 orifices. However, for maximum impact, the centre nozzle was plugged throughout the experiment. To achieve a desired configuration and number of nozzles, the remaining 6 orifices were fitted with either plugs or flat-fan nozzle atomizers (See Figure 3.6a).

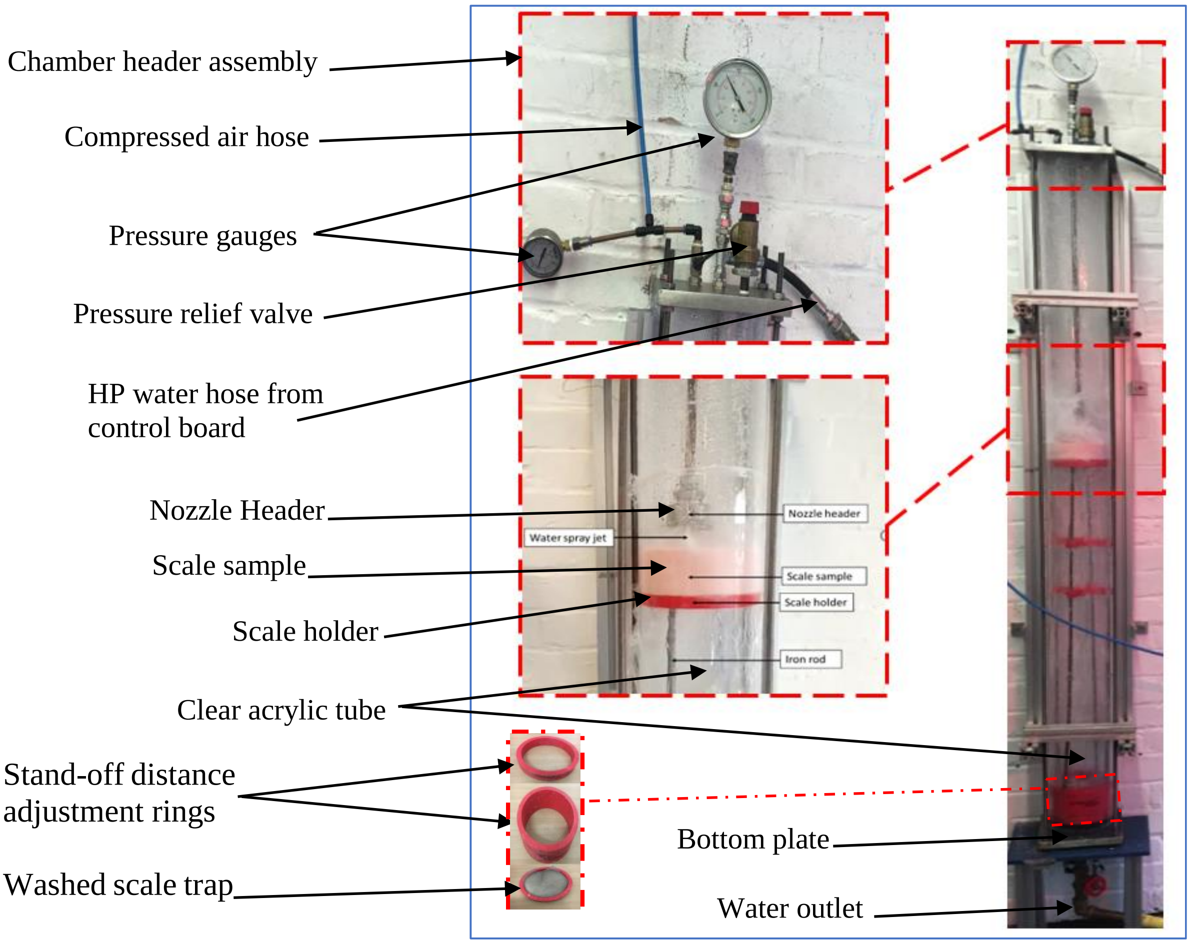



Figure 3.5: The Descaling Chamber.

The scale holder terminates on two pieces of cylinders/rings (with heights of 25mm and 50mm) used to adjust the distance of the scale from the atomizer. When both rings are placed below the scale holder, the scale is only 25mm away the stand-off distance is 25mm from the atomizer. When none of them is used, the scale is 75mm away from the atomizer and when only the 25mm long ring is placed below the scale holder, the stand-off distance is 50mm. This distance is called the **stand-off distance.** Just below the stand-off distance adjustment rings and before the exit is a wire mesh called the Washed scale trap. It prevents scale debris from flowing down the water outlet and therefore, prevents possible clogging of the water outlet.

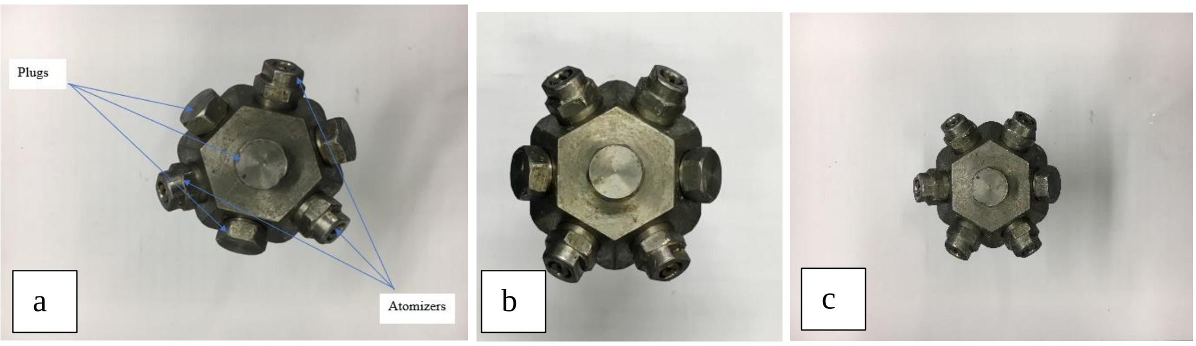



Figure 3.6: Nozzle Headers Showing: (a) Triangle configuration with 3 Atomizers and 3 Plugs; (b) Rectangle configuration and (c) Pentagon configuration

The pattern of the arrangement of the atomisers is termed **Nozzle Configuration.** The nozzle configuration in Figure 3.6a is called Triangle (obtained by linking the tip of the 3 atomizers with straight lines).

#### 4. Control Board

The control board is magnified in Figure 3.7. It provides instrumentations for the regulation and measurement of the rates of flow of water and compressed air.

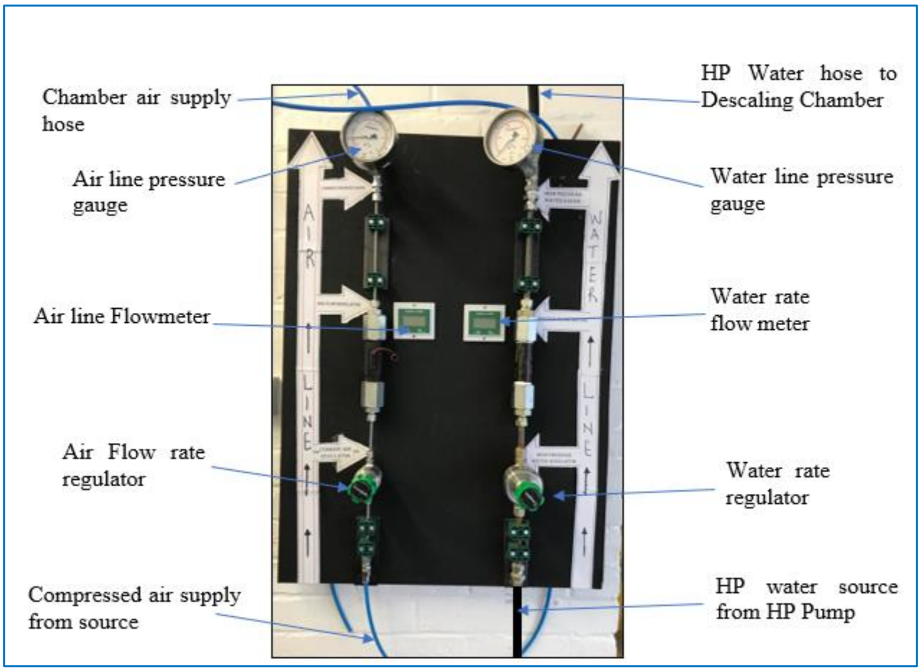



Figure 3.7: The Control Board

5. **High-Pressure Water Pump.**

The High-Pressure (HP) water pump is an 8.22 type, Oil Shell Tellus 150 pump with a maximum pump speed of 1250rev/min, maximum working pressure of 4000psi or 276bar and maximum working flow of 15.9gal/min. It was constructed in 2010. Its front and rear views are shown in figure 3.8.

Figure 3.8: Front View (*Left*) and Back View (*Right*) of the High-Pressure Water Pump.

### 3.4.4 Experimental Procedure

The Descaling experiment comprises of three phases: (i) rig calibration and (ii) scale removal at ambient chamber condition and (iii) scale removal at compressed chamber condition.

#### 3.4.4.1 Rig Calibration

This stage involves the calibration of the entire circulation system. Specifically, the objectives of this stage of the experiment were to: (i) measure the mass flow rates of water jets through nozzle headers and use them to check the accuracy of the pressure gauges and flow meters; (ii) estimate the time-to-fill-up of the descaling chamber for use in setting experimental run time; (iii) ensure the integrity of the system and repair any leakages or loose fittings; (iv) Have an estimate and idea of the possible pressure values at each node (the pump, control board, descaling chamber).

The rig calibration was done as follows:

i. The experimental set up was coupled as shown in Figures 3.4 through 3.8 using five nozzles that were fitted into the nozzle headers with the use of 5 atomizers.
ii. The pump was turned on and a timer was set to obtain pressure build-up time.

iii. Using the Water rate regulator on the Control board, the water line was opened, and pressure rose to 48 bar (gauge).
iv. After pressure stabilized, the build-up time was recorded, and flow continued for another 2minutes.
v. The mass of the water drained after 2minutes was measured and recorded.
vi. The steps (iv), (v) and (vi) were repeated two more times to ensure repeatability.
vii. The number of nozzles was reduced by one, by replacing an atomizer with a plug (see Figure 3.6) and the above steps were repeated until only 3 nozzles were left. It was difficult to control the pressure beyond 3 nozzles.
viii. Steps (i) through (vii) were repeated at 60bar and 100bar pump pressures.

The result of rig calibration is presented in Table A1 of Appendix A and used to estimate the mass flow rates at 4.8MPa, 6MPa and 10MPa using Equation 3.1. The mass flow rates are shown in Tables A1 through A3 of Appendix A:

$$Mass\ flow\ rate_{after\ build-up} = \frac{Mass\ of\ water_{after\ build-up}}{2\ minutes} \tag{3.1}$$

The residence time of water, at the maximum pressure of 10 MPa, in the Descaling chamber was calculated using Equation 3.2 as follows:

$$Residence\ time\ of\ water = \frac{Volume\ of\ tube}{Volumetric\ flow\ rate} \tag{3.2}$$

The volume of the chamber tube was calculated as:

$$V = \frac{\pi D^2}{4} = \frac{\pi \times (0.15)^2 \times 2}{4} = 35 \times 10^{-3} m^3 = 35.3\ litres \tag{3.3}$$

The volumetric flow rate was obtained from the atomizer chart (Appendix C). The maximum flow rate was taken at 10 MPa as 11.3 litres/min. Then the residence time was estimated as:

$$Residence\ time\ of\ water = \frac{Volume\ of\ tube}{Volumetric\ flow\ rate} = \frac{35.3}{11.3} = 3.12\ min$$

From the result of residence time above, the experimental run time was set at 3 minutes for all runs.

#### 3.4.4.2 Scale Removal Experiment (Ambient Chamber Condition)

Ambient condition, in this scenario, refers to the absence of any aeration or compression in the tubing chamber and this stage of the Descaling experiment attempts to simulate scale removal from production tubing at the prevailing pipe condition. In this case, the descaling chamber is at Metric Standard Conditions (MSC). Although this scenario is hardly realistic, the experiment provides us with a base or reference line for the next stage of the experiment – scale removal at compressed chamber condition – which more closely mimics the condition inside a production tubing

The process diagram in Figure 3.9 shows the arrangement of materials, instruments and apparatuses employed in the descaling trials under ambient chamber condition. As earlier mentioned, this experiment simulates the removal of paraffin scales deposit along production tubing, when it is not entirely blocked by the waxes, by only freshwater.

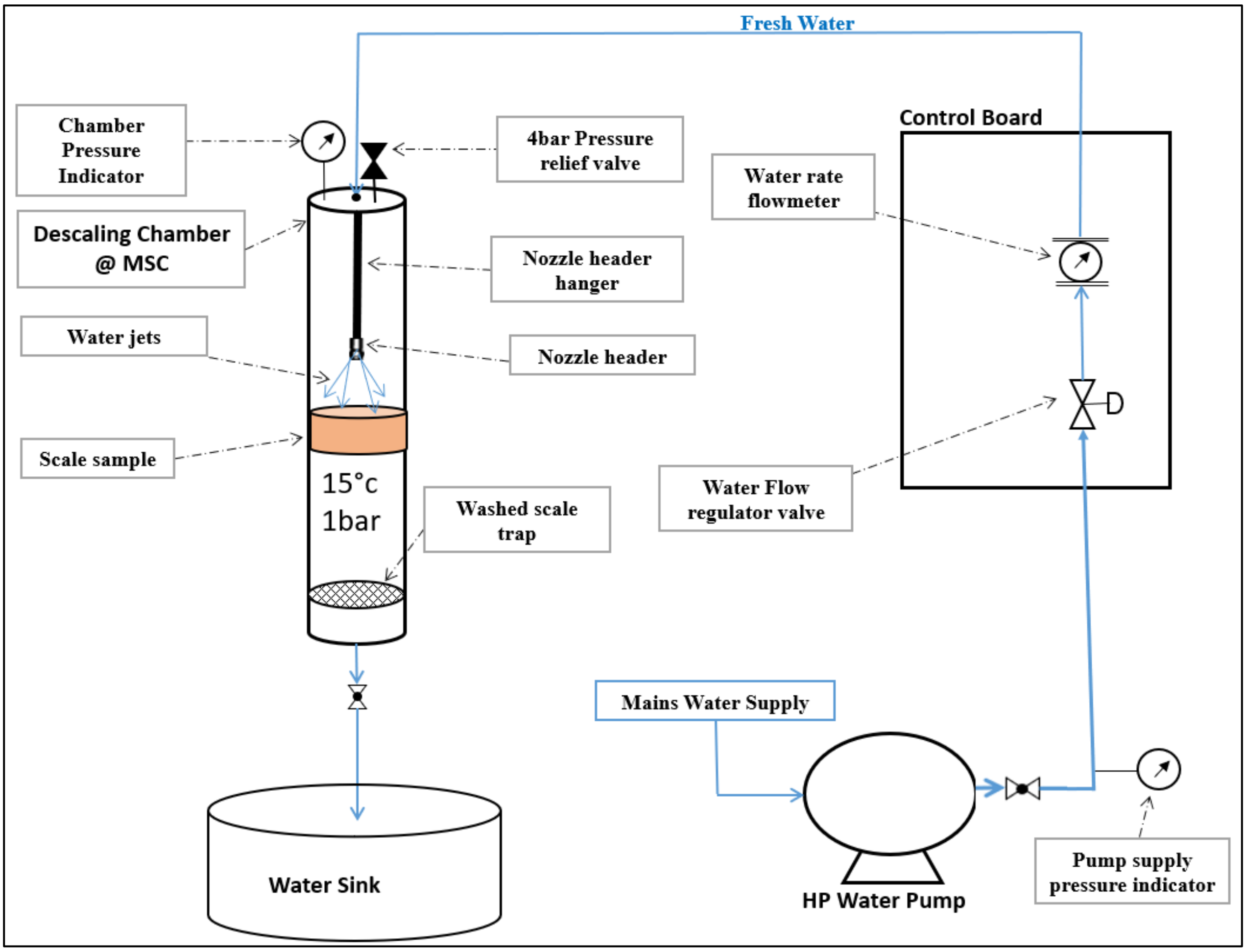



Figure 3.9: Process Diagram of Scale Removal Experiment at Ambient Chamber Condition

In Figure 3.9, freshwater from the mains water supply is sprayed on the scale sample, at the indicated chamber condition, to remove it. The steps followed in performing this experiment are as follows:

I. An experimental design was done such that 27 experimental trials were assigned values of experimental variables namely: number of nozzles, stand-off distance, injection pressure and nozzle configuration.

II. A scale sample was allotted per experimental trial or run, and the Scale ID or Scale reference was recorded against the trial number.

III. Scale samples were weighed and their masses before spraying was recorded against the trial number. This update the experimental design to the golden coloured columns (Column 2 to Column 9) of Table A2 in Appendix A.

IV. The image of each scale was taken and recorded before the spraying.

V. For the first experiment, run 1 (Row 2, Table A2), 5 atomizers were fitted on the nozzle header to obtain a pentagon configuration as described in Figure 3.6.

VI. The corresponding scale sample (17-SH in this case) was placed on the holder.

VII. The corresponding stand-off distance (25mm in this case) was obtained by placing only the 50mm Stand-off distance adjustment ring between the Scale holder and the Bottom plate of the Descaling chamber (Figure 3.5).

VIII. The Washed scale debris trap was placed between the water outlet and the Stand-off distance adjustment ring.

IX. The Acrylic tube was gently placed on the bottom plate such that the Scale sample, holder and Washed scale traps were inserted into the tube.

X. The Chamber header assembly was then gently fitted on the acrylic tube.

XI. The Descaling chamber is then adjusted and secured properly for structural integrity and to ensure that a watertight column is created when the water outlet valve is closed.

XII. The HP pump was then switched on and freshwater was sprayed on the scale sample at the pressure corresponding to this Run (4.8MPa) for 3minutes.

XIII. The scale sample was then removed from the chamber and an image of the scale was taken and recorded.

XIV. The scale sample was then subjected to 12 hours of indoor drying. After which it was weighed, and the mass was recorded against the experimental run number and scale reference number.

XV. The Washed scale trap/sieve (Figure 3.5) was cleaned of the debris removed from the scale sample.

XVI. Steps (I) to (XV) are repeated for the remaining 26 experimental trials (Runs 2 to 27, Table A2, Appendix A) using the specified parameters and corresponding scale in the experimental design for each run.

XVII. The Mass of Scale Removed was obtained as the difference between its mass before the spraying and its mass after the spraying when the scale is eroded, and/or a hole is made in it.

XVIII. Where the scale is broken/shattered, the mass of the largest chunk is used as its mass after the experiment in step (XVII).

XIX. The results are tabulated as shown in Table A2 of Appendix A.

#### 3.4.4.3 Scale Removal at Compressed Chamber Condition

This part of the experiment hopes to investigate the effect that subjecting the scale to compressive force – created due to the aeration of the descaling chamber – will have on the descaling of production tubing with HP, multiple water jets. In Figure 3.10, the 2bar compression in the descaling chamber was obtained by injecting air into it and pressurising it before spraying the scale with HP water.

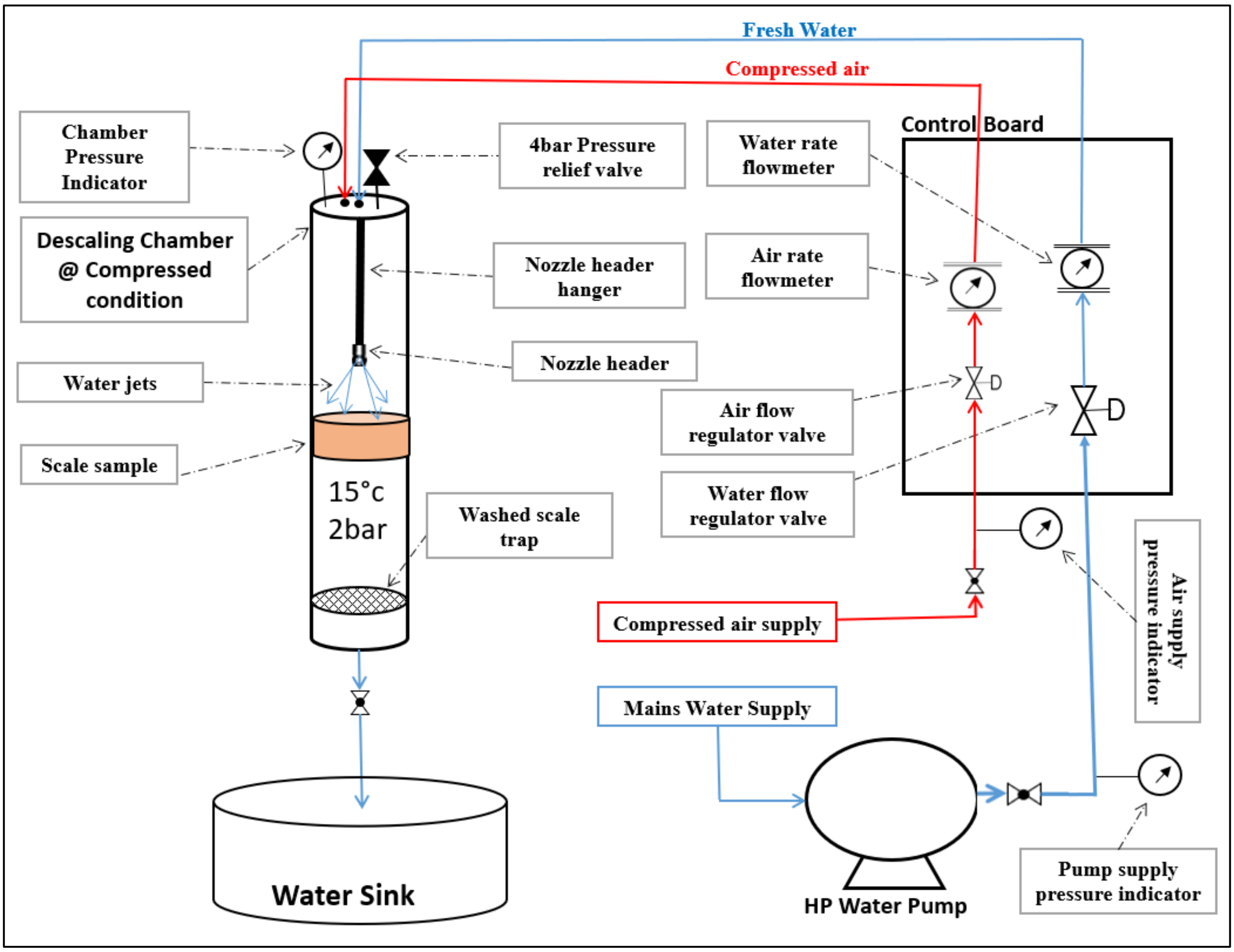



Figure 3.10: Process Diagram of Scale Removal Experiment at Compressed Chamber Condition

The steps followed in conducting this section of the experiment are outlined below.

I. Steps (1) to Step (X) of Section 3.1.6.2 were repeated with 27 new different scales following the Experimental Design (ED) for this experiment. The ED is shown in Table A3 of Appendix A (Yellow columns 2 to 9)

II. A compressed air circulation system was connected to the experimental process as shown in Figure 3.10 and the descaling chamber was coupled to be airtight and structurally stable.

III. The Water outlet valve in the Bottom plate (Figure 3.5) was closed and the compressed air was injected into the chamber until the Chamber pressure gauge (Figure 3.10) indicated a chamber condition of 2bar.

IV. The HP pump was then switched on and freshwater was sprayed on the scale sample at the pressure corresponding to this Run (4.8MPa) for 3minutes.

V. The chamber pressure was kept at 2bar with the use of a column of water to seal off the water outlet; such that a closed, compressive system or environment is maintained around the scale sample even as the water outlet valve is opened and water is circulated during the experimental run time.

VI. At the end of the 3minutes run time, the air supply was cut off and Steps (XIII) to (XVIII) of Section 3.1.6.2 was repeated on this scale sample and with the use of Table A3 (the design for this experiment).

VII. Results were tabulated as shown in Table A3 of Appendix A.

## 3.5 Precautions Taken to Reduce Errors

- Undue increase in the masses of the scale samples could occur after experimental trials due to the absorption of water. To minimize the effect of this, the scale samples were left to dry for 24hours before they were weighed.
- Swabbing of nozzle headers occurred often when the combination of high pressures and small number of nozzles is used. This led to a change in the impact position and velocity of the spray particles. To minimise this, the water pump was operated efficiently following the rig calibration such that pressure fluctuations were reduced.
- Maintaining the chamber condition at 2bar during compression was difficult with the control board. The use of a column of water from the water exit helped to improve consistency with the desired pressure.
- Spraying at high pressures and a higher number of nozzles creates high water flow rates that could lead to submerging of the scale sample before experimental run times elapse. This problem was tackled by stepwise simulation of such trials.

# Chapter 4: Results Presentation, Analysis and Discussion

## 4.1 Introduction

This section of features a comprehensive presentation, analysis and discussion of the results obtained from this study, as described in the previous chapter. As a preamble, the results of the Scale sample testing and validation and Rig calibration (Section 3.3 and Section 3.4.4.1) will be analysed firstly, afterwards, the results of the descaling trials are presented in the order that the experiments were conducted (i.e. at ambient chamber condition and compressed chamber condition), this will be followed by an intensive study of the outcomes of the Descaling experiment with a focus on meeting the objectives of this study listed in Section 1.3. Chronologically, the effect of the Design variables (Columns 2-9 of Tables A2 and A3 of Appendix A) on the performance of scale removal will be examined and analysed.

Since some of the variables are derivatives of other variables, and some are not quantifiable, the number of factors or independent variables to be investigated will reduce from 8 to 4. For instance, the Scale ID and Nozzle configuration are not numerical. and it is a function of the number of nozzles. Therefore, In the place of the two factors, the effect of the number of nozzles on the descaling process will be investigated. Similarly, in the results of the Rig calibration (Table A1, Appendix A), the Mass flow rate is shown to be a derivative of the Injection pressure in Section 3.4.4.1). For this pair, the injection pressure will be used in all the analysis.

## 4.2 Testing of Scale Samples (Physical Model Validation)

Considering that the scale samples were fabricated from household candles which have gone through industrial processes that may have altered the properties of the raw materials (paraffin), this test was conducted to assess the closeness of the scales used in this experiment with paraffin waxes so that the fabricated scales better represent oil field scales. This was done by matching established cooling curves of paraffin waxes with cooling curves of the fabricated scales.

In Figure 4.1, the cooling curve of the fabricated scales was matched with the cooling curve of paraffin waxes published by (EDGE, 2013) which was obtained from an analysis of 100% pure paraffin wax, and the curve of (Hasan et al., 2016). The scale samples show excellent qualitative (pattern) and qualitative match with the first model and a good pattern match with the curve of (Hasan et al., 2016). The reduction in the temperature of cooling of the Hasan et al. wax is because their paraffin was subjected to increased ventilation for meeting the aim of their study.

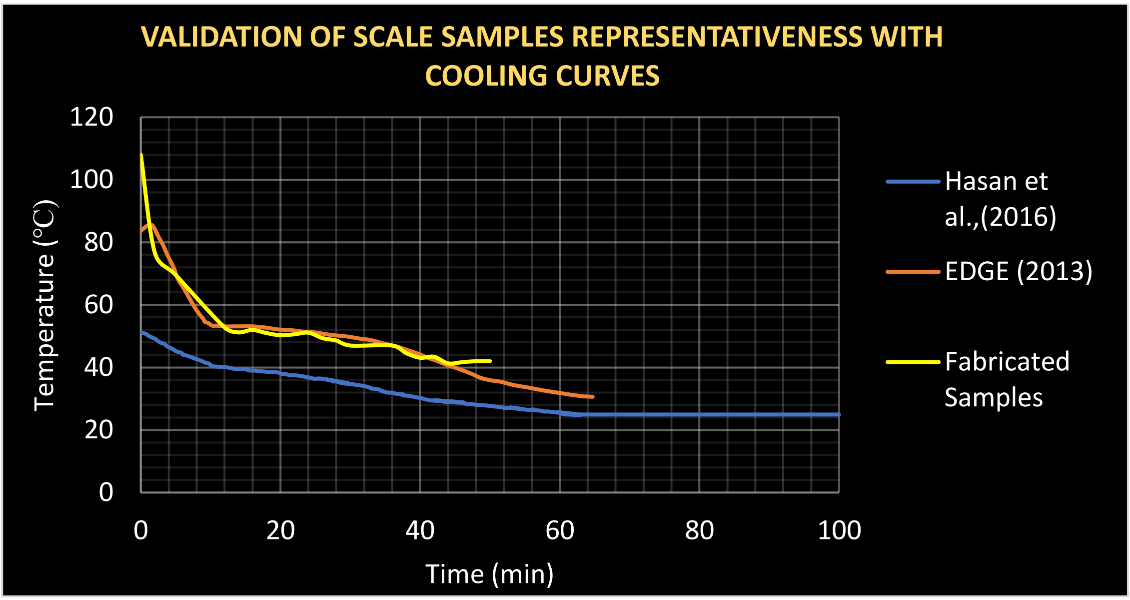



Figure 4.1: Validation of Scale Samples Representativeness with Cooling Curves

## 4.3 Effect of Water Injection Rate on Mass Flow Rate of Water.

The relationship between the mass flow rate of water and the injection rate is best analysed from the results of the Rig calibration presented in Table A1 and Figure 4.2. The plot confirms that increasing the injection rate of water increases the amount of water injected for all three cases while the rate of the increase in mass flow of water increases with increase in the number of nozzles. In other words, the lower the number of nozzles, the higher the pressure that will be required to inject a certain amount of water per unit time. This is attributable to the fact that back pressure and resistance to flow reduces as the water exits (atomisers or nozzles in this case) increase and vice versa.

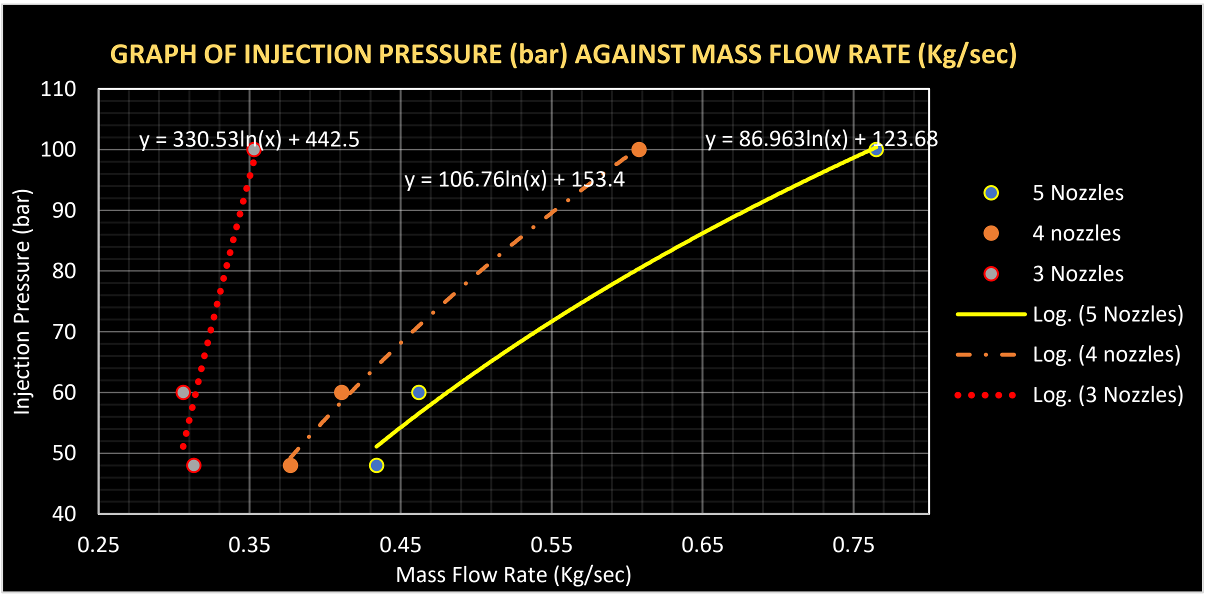



Figure 4.2: Relationship between Injection Rate of Water and Mass Flow Rate of Water

## 4.4 Presentation of Scale Removal Trials Results

In this section, the results of the descaling trials tabulated in Table A1 and Table A2 of Appendix A, for the Descaling at ambient chamber condition and Descaling at compressed chamber condition trials respectively, are presented graphically for easier visualisation and analysis.

### 4.4.1 Results of Scale Removal at Ambient Chamber condition.

This section presents the results of the scale removal trial described in Section 3.4.4.2 in Figures 4.3 through 4.5. In a few words, the descaling trials in this case, which follow the experimental design shown in Table A1 of Appendix A, were carried out without any air supply into the Descaling chamber. Therefore, the chamber conditions, in this case, is ambient or Metric Standard Conditions (MSC).

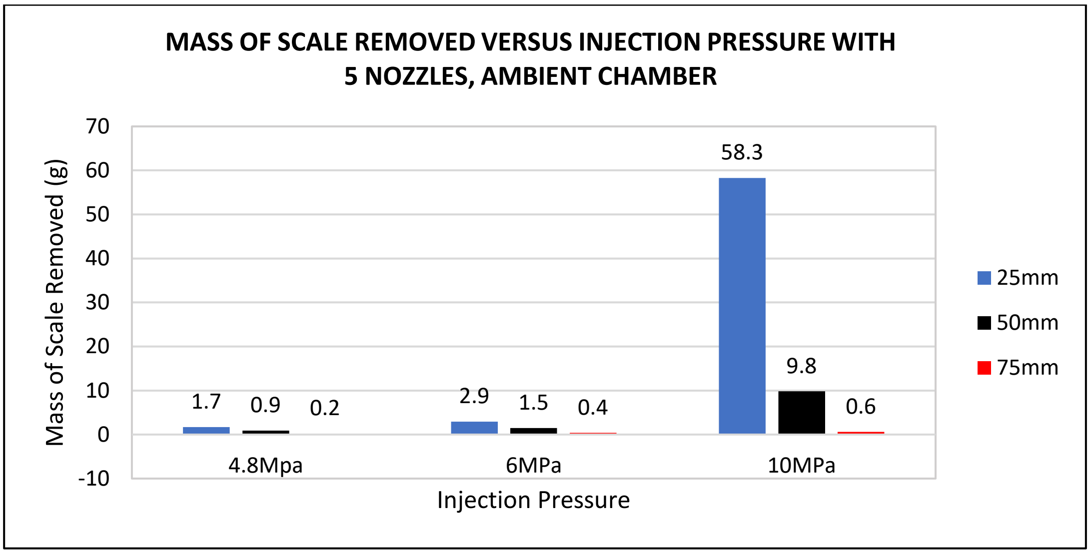



Figure 4.3: Results of Descaling Trial at Ambient Chamber Condition with 5 Nozzles.

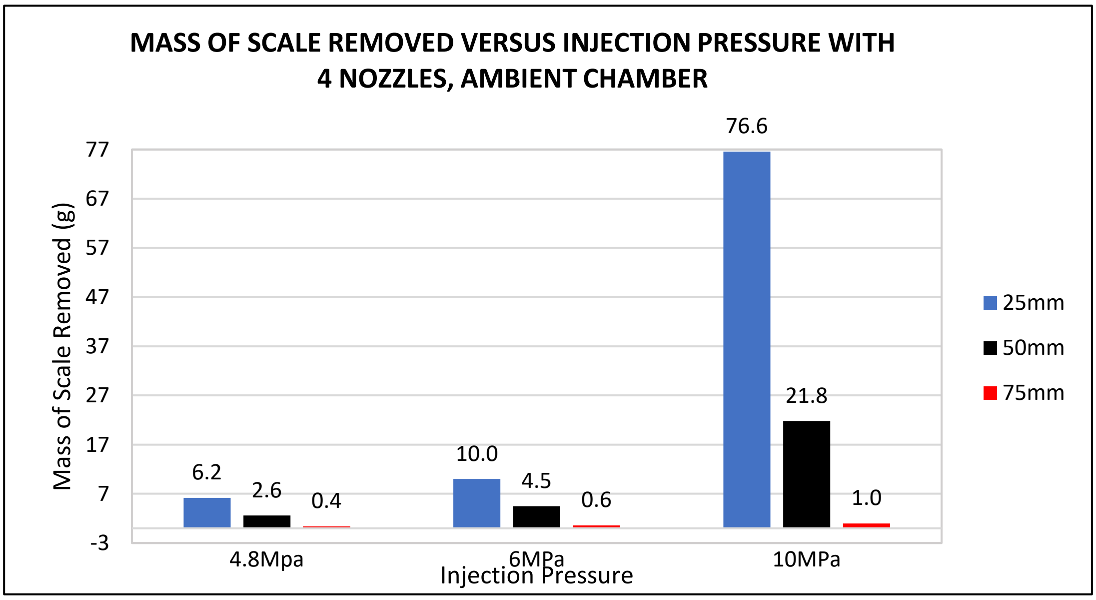



Figure 4.4: Results of Descaling Trial at Ambient Chamber Condition with 4 Nozzles.

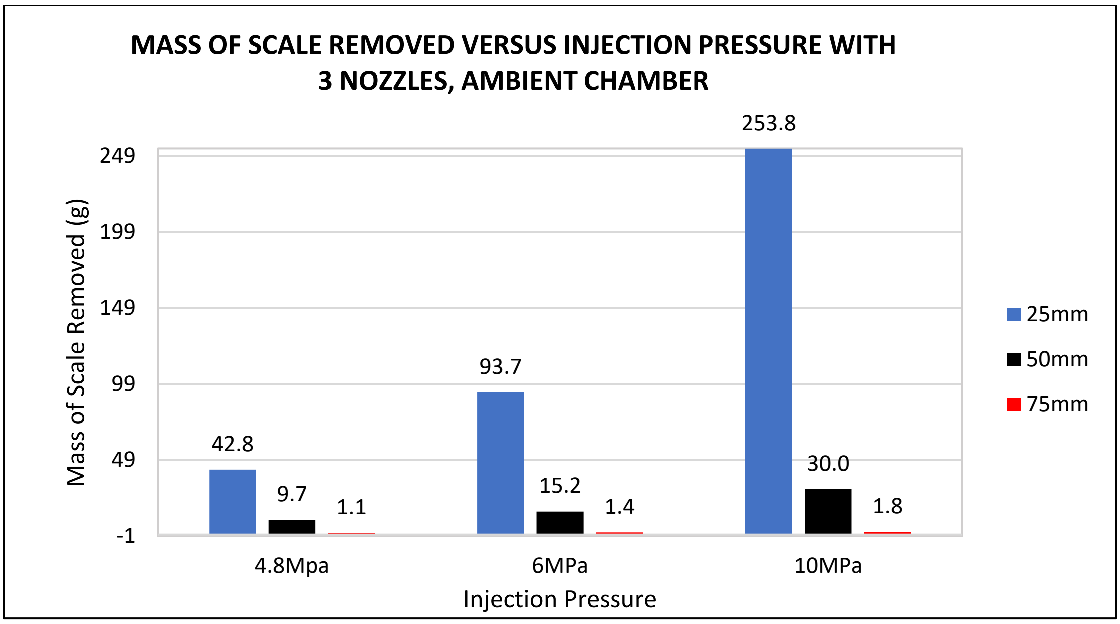



Figure 4.5: Results of Descaling Trial at Ambient Chamber Condition with 3 Nozzles.

The impact of the spraying on the scale samples are shown in Appendix B (Figure B1 for 5 Nozzles, Figure B2 for 4 Nozzles and Figure B3 for 3 Nozzles), where pictures of all the scale samples used in this experiment are presented before and after they were subjected to the experimental trial assigned to them in the experimental design (Table A2, Appendix A).

### 4.4.2 Results of Scale Removal at Compressed Chamber condition.

This section presents the results of the scale removal trial described in Section 3.4.4.3 in Figures 4.6 through 4.8. The descaling trials, in this case, follow the experimental design shown in Table A2 of Appendix A. They were carried out with air supply into the Descaling chamber such that the Chamber pressure is increased and maintained at 2bar.

The impact of the spraying on the scale samples are shown in Appendix B (Figure B4 for 5 Nozzles, Figure B5 for 4 Nozzles and Figure B6 for 3 Nozzles), where pictures of all the scale samples used in this experiment are presented before and after they were subjected to the experimental trial assigned to them in the experimental design (Table A3, Appendix A).

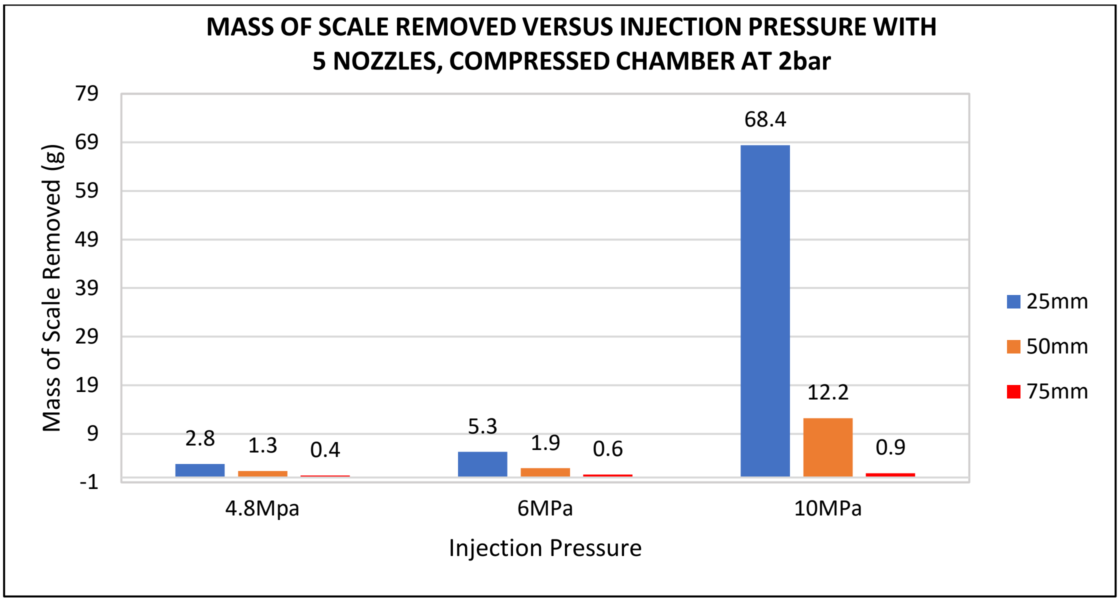


Figure 4.6: Results of Descaling Trial at Compressed Chamber Condition with 5 Nozzles.

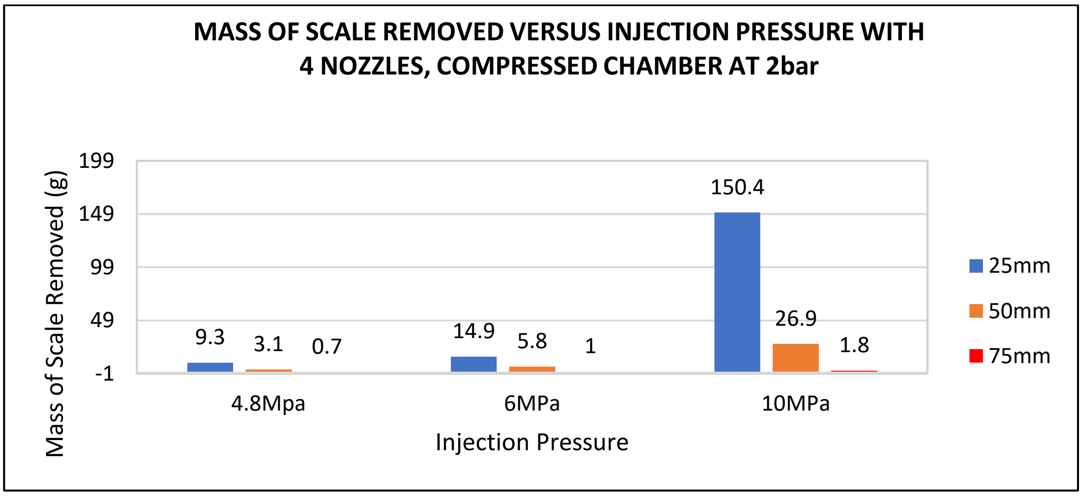


Figure 4.7: Results of Descaling Trial at Compressed Chamber Condition with 4 Nozzles

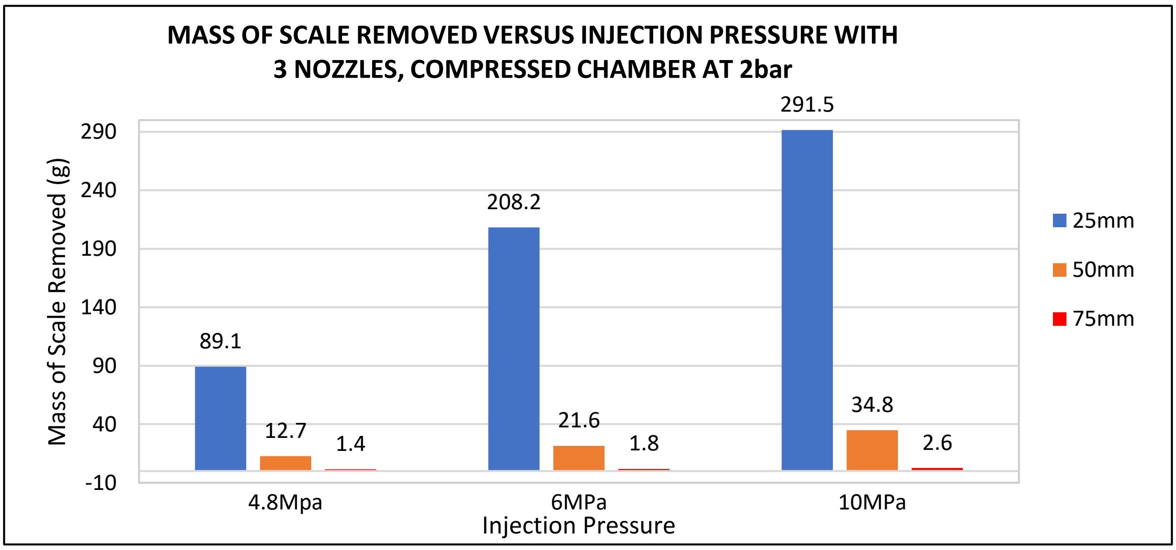


Figure 4.8: Results of Descaling Trial at Compressed Chamber Condition with 3 Nozzles

## 4.5 Analysis and Discussion of Scale Removal Trials Results

Essential in the performance of the water jet, or its impact, on the mass of scale removed are the quantitative design variables utilised in this work: (i) mass flow rate; (ii) injection pressure; (iii) descaling chamber condition (quantified as ambient pressure of 1bar and compression to 2bar); (iv) the number of nozzles and (v) stand-off distance. As explained in the Introductory section (Section 4.1), the injection pressure can be a surrogate for the mass flow rate such that four factors are left to be analysed. In Section 4.6 and Section 4.7, the effects of the number of nozzles and chamber condition on scale removal are investigated while the remaining two factors are studied in this section.

### 4.5.1 Effect of Stand-off Distance on Scale Removal Efficiency.

The Stand-off distance or Spray distance is the vertical distance between the centre of the atomizer or jet nozzle and the scale. Figure C2 and Figure C3 explain that the velocity, and hence, the impact force of the spray particles depreciates as the spray distance increase (See Appendix C). i.e., the water jets will have more scale removal ability at 25mm spray distance than at 75mm spray distance. This is obvious in the outcomes of all six descaling trial results shown in Figures 4.3 to Figure 4.8 and evident in the pictorial results presented in Appendix B.

In Figure 4.3, for instance, the mass of scale removed with 5 nozzles at the least injection pressure of 4.8MPa increased by 0.5g for a 25mm reduction in spray distance and 1.5g for a further reduction of 25mm. This is more conspicuous at the upper injection pressure boundary – 10MPa – where reducing the spray distance from 75mm to 25mm caused an additional 57.7g of scale to be removed, a 96% increase in the scale removal efficiency. In the corresponding qualitative result (Figure B1, Row 4), this impact is shown to progress from mere surface erosion of the scale sample to breaking the scale sample into three pieces. This trend is common to all the experimental runs for both chamber conditions and more pronounced when the chambers are compressed as shown in Figure 4.9 which shows the scale removal at ambient chamber condition for different numbers of nozzles and Figure 4.10 which presents the same information for compressed chamber condition.

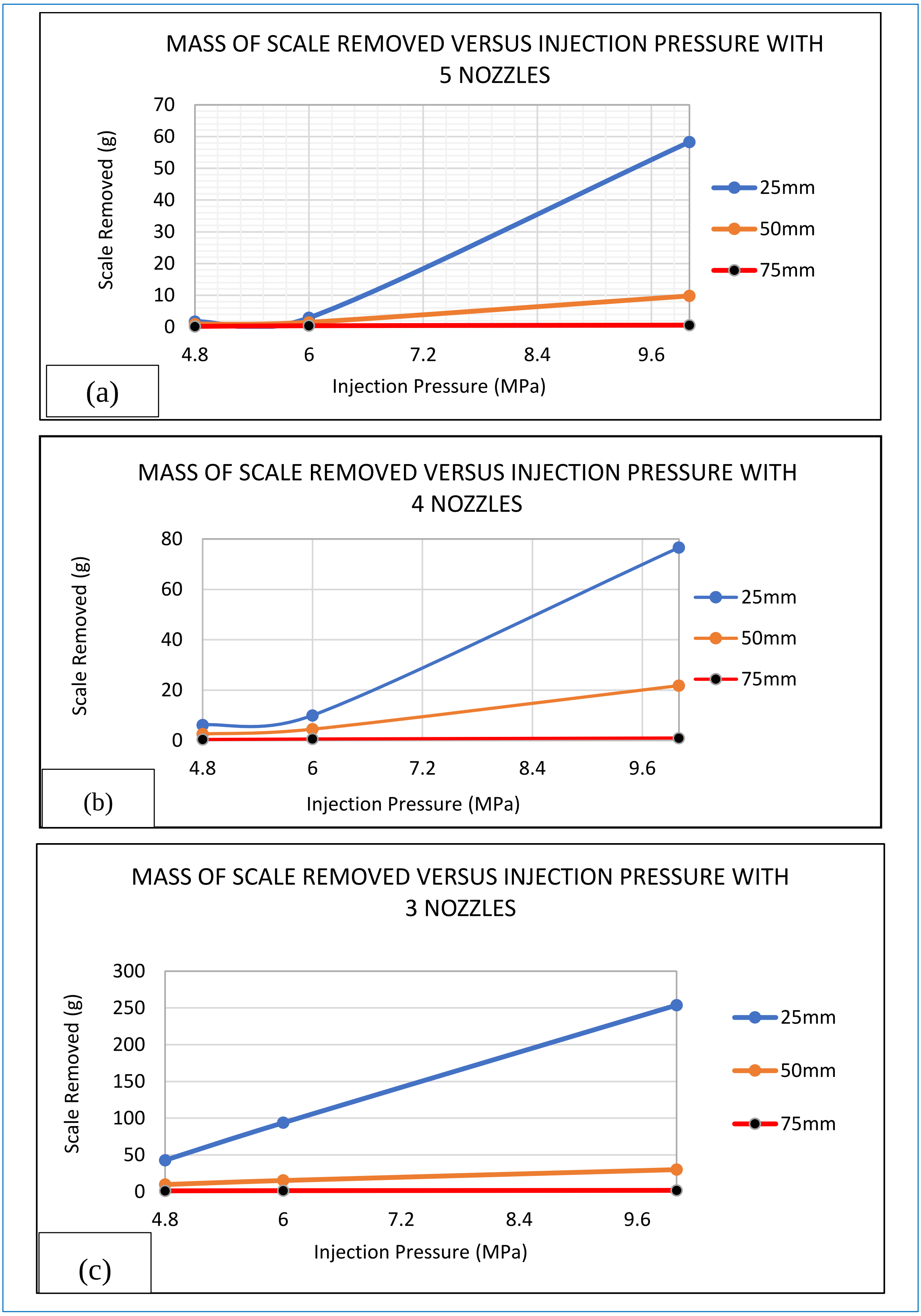



Figure 4.9: Effect of Stand-Off Distance on Scale Removal at **Ambient Chamber Condition.**

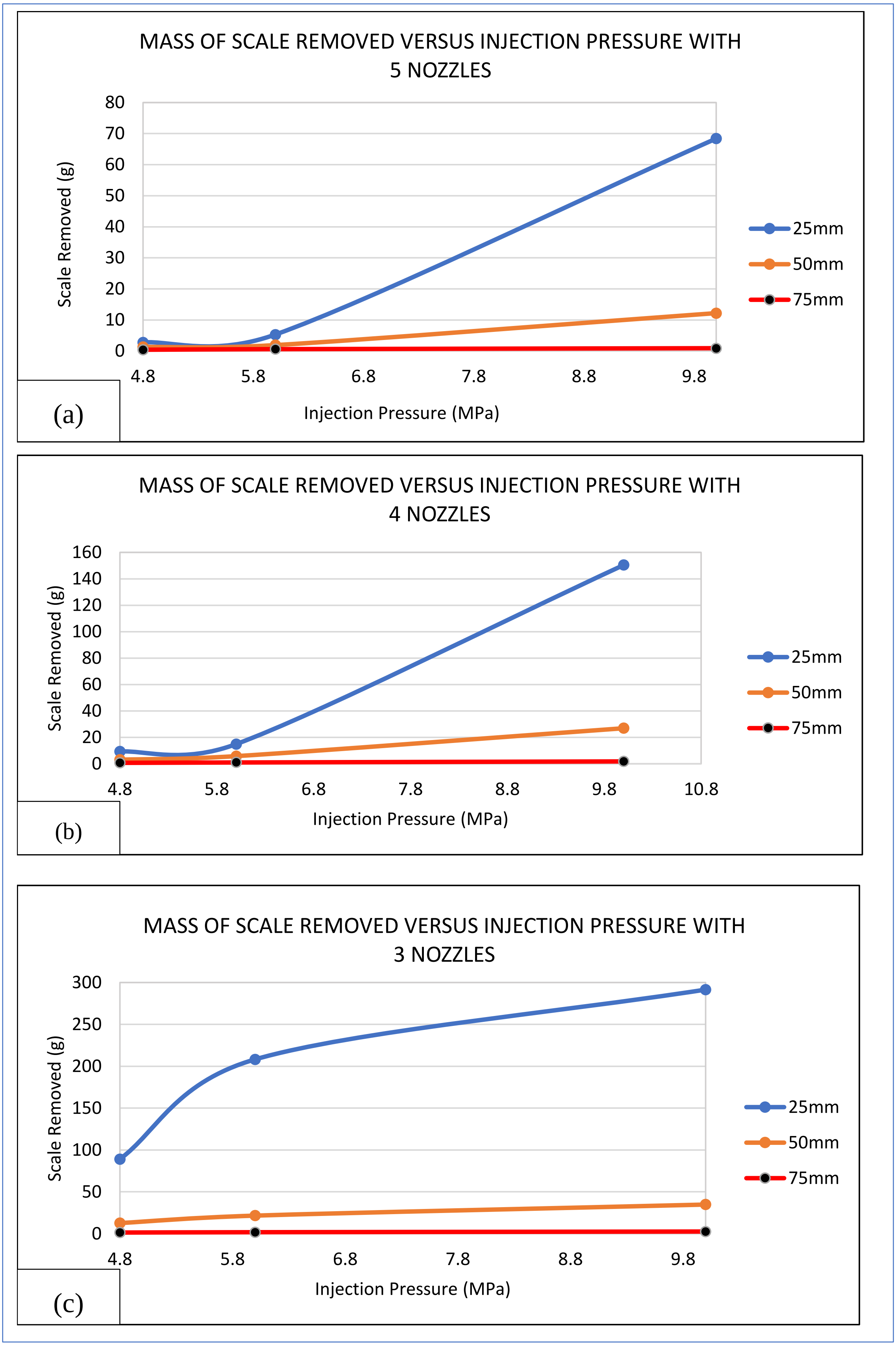



Figure 4.10: Effect of Stand-Off Distance on Scale Removal at **Compressed Chamber Condition.**

### 4.5.2 Effect of the Spray Injection Pressure on Scale Removal Efficiency.

To study the role of water injection pressure in scale removal with only multiple HP water jets from flat-fan nozzles, the amount of scale removed at different injection pressures was investigated at different stand-off distances or spray distances using 3, 4 and 5 nozzles at the two chamber conditions being investigated in this work. The outcome is presented in Figure 4.11 for the ambient chamber case and Figure 4.12 for the compressed chamber case.

At a glance, Figure 4.11 and Figure 4.12 establish that, for a given number of nozzles, the amount of scale removed increases as the water injection pressure increases. This is noticeably true for all cases (spray distances) when three and four nozzles were used at both ambient and compressed chamber conditions. However, when five nozzles were used, at the least spray distance of 25mm, at both ambient and compressed chamber conditions, little or no difference existed between the amounts of scale removed at 4.8MPa injection pressure and 6.0MPa injection pressure and the extra amount of scale removed by increasing the pressure from 6.0MPa to 10MPa reduced from 66.6g at 4nozzles to 57.4g at 5nozzles in the ambient chamber case (Figure 4.11a). In the compressed chamber counterpart (Figure 4.12a), this difference fell from 135.5g to 63.1g.

The higher scale removal at higher pressure values can be explained by the fact that the mass flow rate of water increases with increase in pressure (as seen in Figure 4.2) and more contact is made on the scale by the water jets over a given duration of spray at a higher pressure for a given number of nozzles and stand-off distance. Consequently, all things being equal, more erosional effect will be produced at high pressures due to the increase in mass flow rate with an increase in the injection rate of water.

While the above assertion is generally acceptable, the increase in the scale removal ability of the water jets with increasing pressure was found to reduce with increasing stand-off distances. This is quickly noticeable in the qualitative results of Appendix B. In Figure B3, for instance, subjecting the scale sample to spraying at 4.8MPa created holes in the scale sample (4SH) after the experiment at 25mm spray distance (Column 4, Row 2). When this pressure was increased to 6.0MPa at the same stand-off distance, the scale sample (15-SH) was broken (Column 4, Row 3). Contrary to this increase in severity of scale deformation by water injection pressure increment, the scale sample at 4.8MPa (34SH) suffered the same deformation (by physical inspection) of holes as the scale sample at a higher pressure of 6.0MPa (29SH), at a higher stand-off distance of 50mm, after the experiment. Similarly, at 75mm spray distance, scale number 45SH was merely eroded, and when the pressure was increased to 60MPa at the same stand-off distance, scale number 52SH also suffered surface erosion.

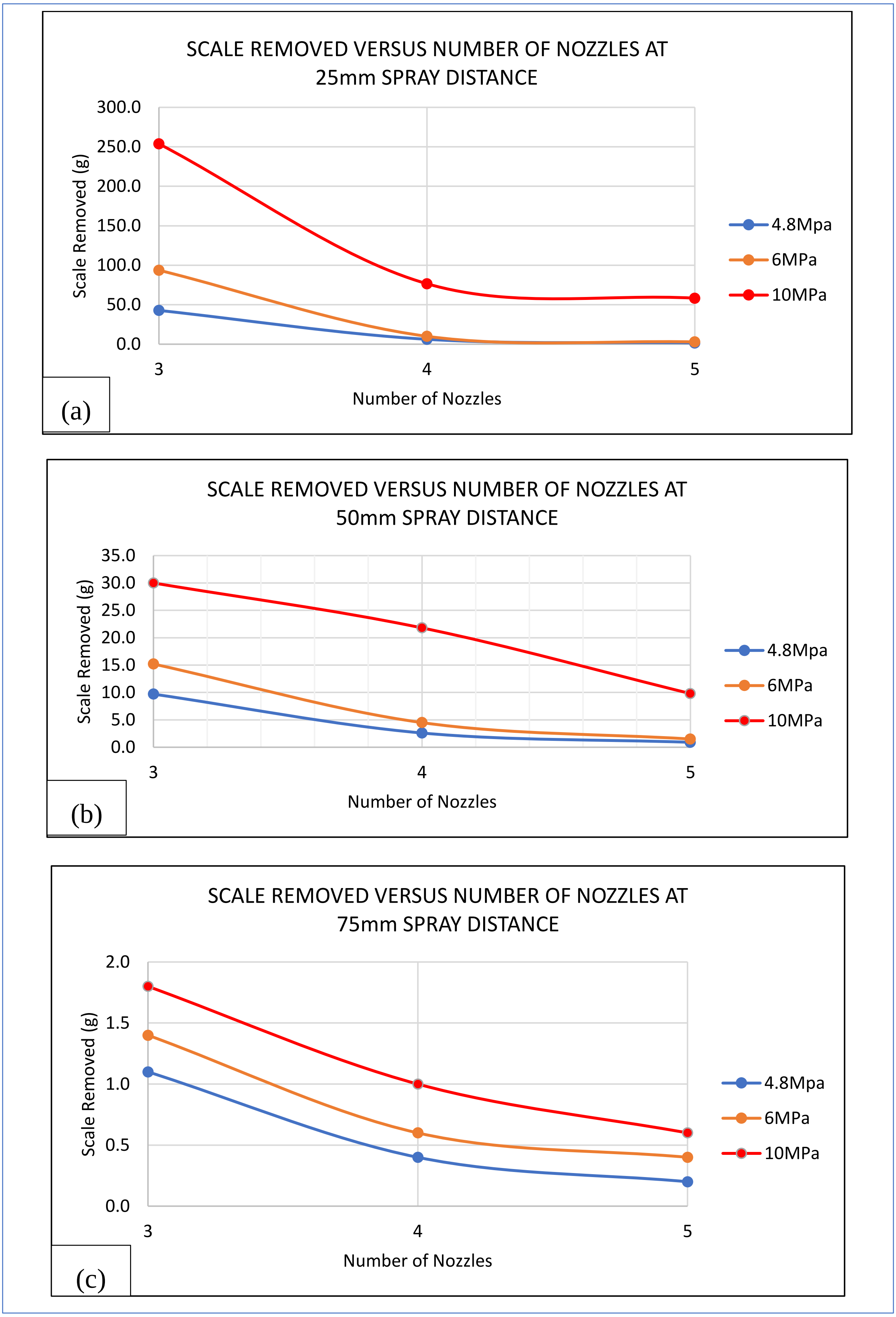



Figure 4.11: Amount of Scale Removed at different Spray Injection Pressures and Number of Nozzles at **Ambient Chamber Condition**

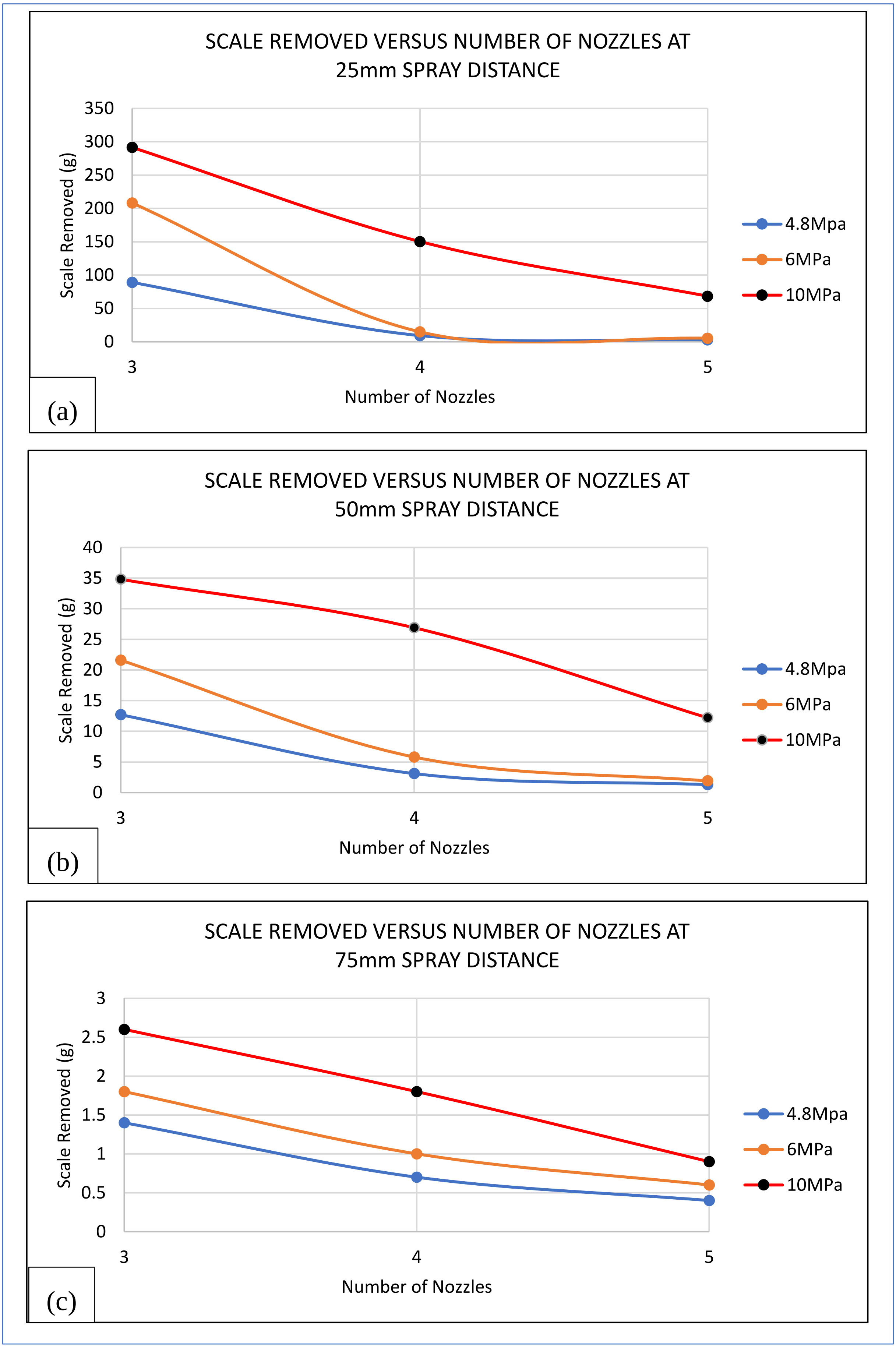



Figure 4.12: Amount of Scale Removed at different Spray Injection Pressures and Number of Nozzles at **Compressed Chamber Condition**

### 4.5.3 Effect of the Use of Multiple Nozzles and Increasing Number of Water Jets on Scale Removal Efficiency

A similar work by (Abbas, 2014) has shown the performance of a single flat-fan nozzle for paraffin scales removal at 25mm stand-off distance at both ambient condition and compression with air to about 12% of the chamber content (air and water). In this section, the outcome of that study is compared with the performance of multiple flat-fan nozzles for the same task, at the same values of the descaling parameters, as obtained from this work (Section 4.4), along with an analysis of the impact of increasing the number of nozzles on the mass of scale removed. Figure 4.13 and Figure 4.14 compares the performance of the proposed descaling approach – the use of only HP water jets – when a single jet nozzle or single spray is used at 25mm stand-off distance with its performance when multiple jet nozzles or multiple flat-fan water sprays are used at the same stand-off distance at ambient and compressed chamber conditions respectively.

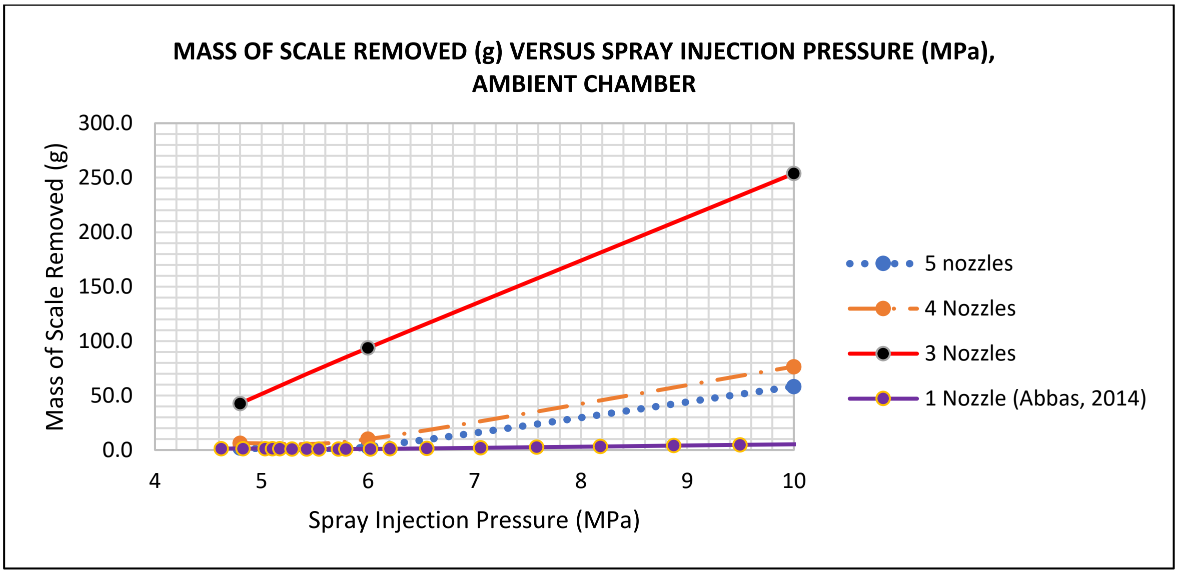



Figure 4.13: Scale Removal with Single Spray Versus Scale Removal with Multiple Sprays at Ambient Chamber Condition

In Figure 4.15, the additional (or less) mass of scale that was removed by the multiple sprays, more than the performance of a single spray is displayed. From the plots, we can deduce that the use of multiple sprays, in most cases, outperform the use of a single spray for scale removal with only HP flat-fan spray. Incremental scale removal can be as high as 248.5g when three nozzles are used at ambient chamber condition and 217.6g when the same number of nozzles are used at compressed descaling chamber condition.

While an increment in the amount of scale removed with multiple nozzles, relative to the use of a single nozzle is consistent and significant for the case of three nozzles for both ambient and compressed chamber conditions, the trends were different for 4nozzles and 5nozzles, especially at compressed chamber conditions where scale removal with multiple nozzles was less favourable at 4.8MPa and 6.0MPa.

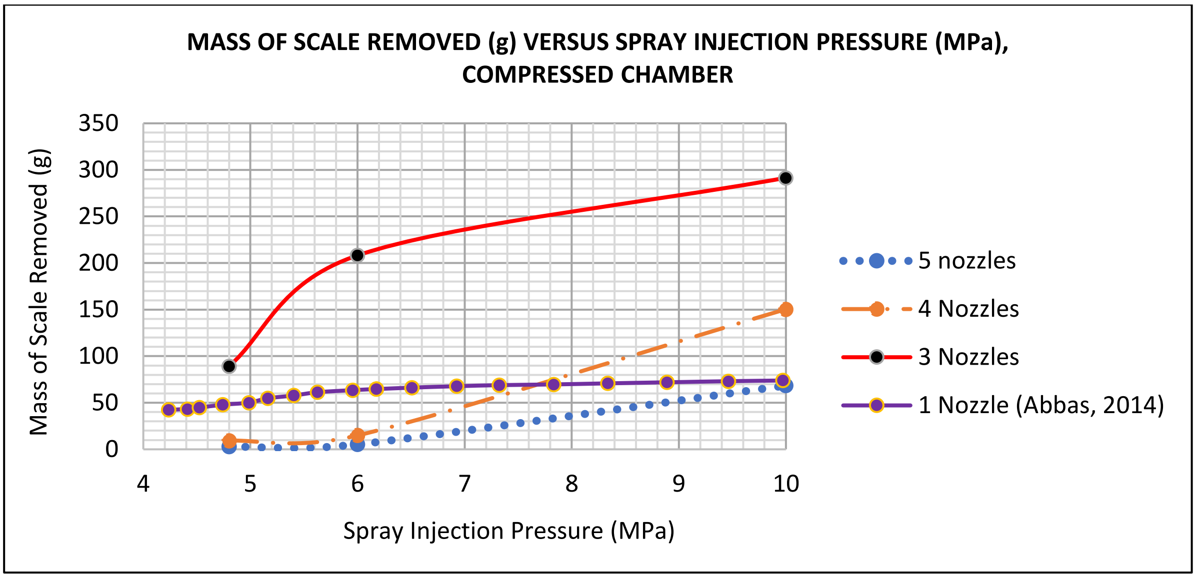



Figure 4.14: Scale Removal with Single Spray Versus Scale Removal with Multiple Sprays at Compressed Chamber Condition

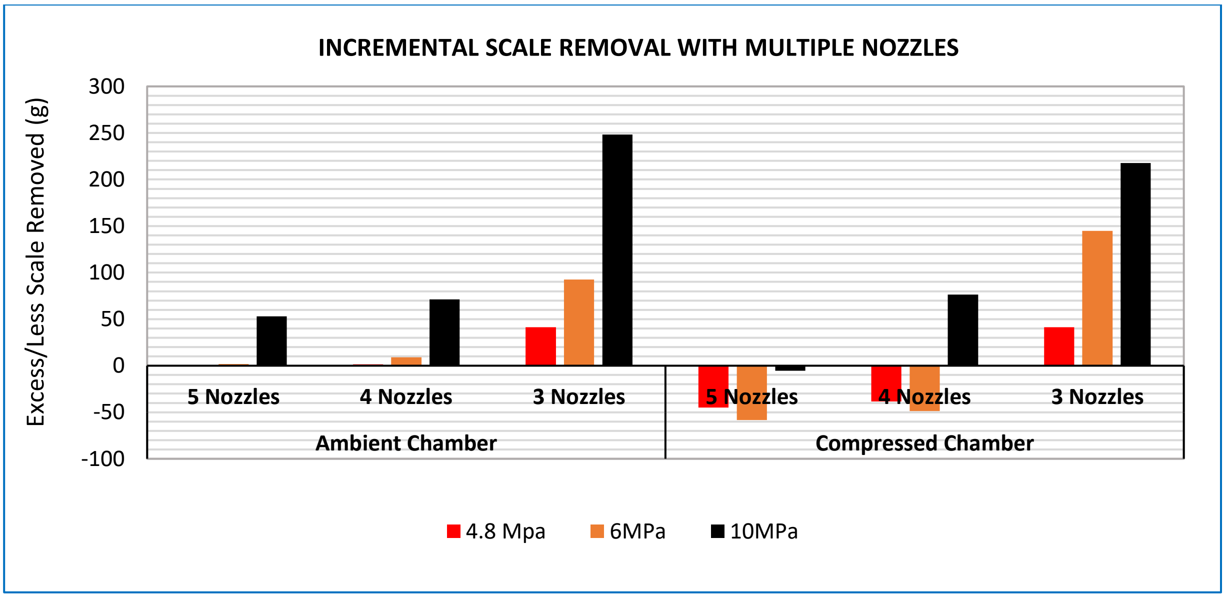



Figure 4.15: Additional Scale Removed by Multiple Sprays in Excess/Less of Scale Removed with 1 Spray

This reduction in the amount of scale removed with the increasing number of multiple nozzles, also evident in Figure 4.11 and Figure 4.12, can be explained by the Bernoulli's principle which speculates that the speed of fluid will increase with a decrease in its potential or increase in resistance on its flow path. In this case, the reverse happens as the impact velocity of the spray particles is reduced by the additional increment in the equivalent cross-sectional area of flow at the atomizers with an increasing number of nozzles in accordance with equation 4.1.

$$u = q/a \quad \ldots\ldots \quad \ldots\ldots \quad \ldots\ldots \quad \ldots\ldots \quad \ldots \qquad \text{Equation 4.1}$$

Where: $u$ = fluid velocity ($m/s$)

$q$ = volumetric flow rate ($cu.m/s$)

$a$ = cross-sectional area of flow ($sq.m$)

### 4.5.4 Effect of Chamber Condition on Scale Removal Efficiency

As described in the procedure for this work (Section 3.4.4), one aspect of the study involves the simulation of production tubing descaling at the in-situ (ambient) conditions of the tubing while the second phase simulates subjecting the tubing (and scale deposits) to compression and investigating the effect of that on the efficiency of the descaling experiment. In this section, the experimental outcomes will be analysed to highlight the effect of the compression.

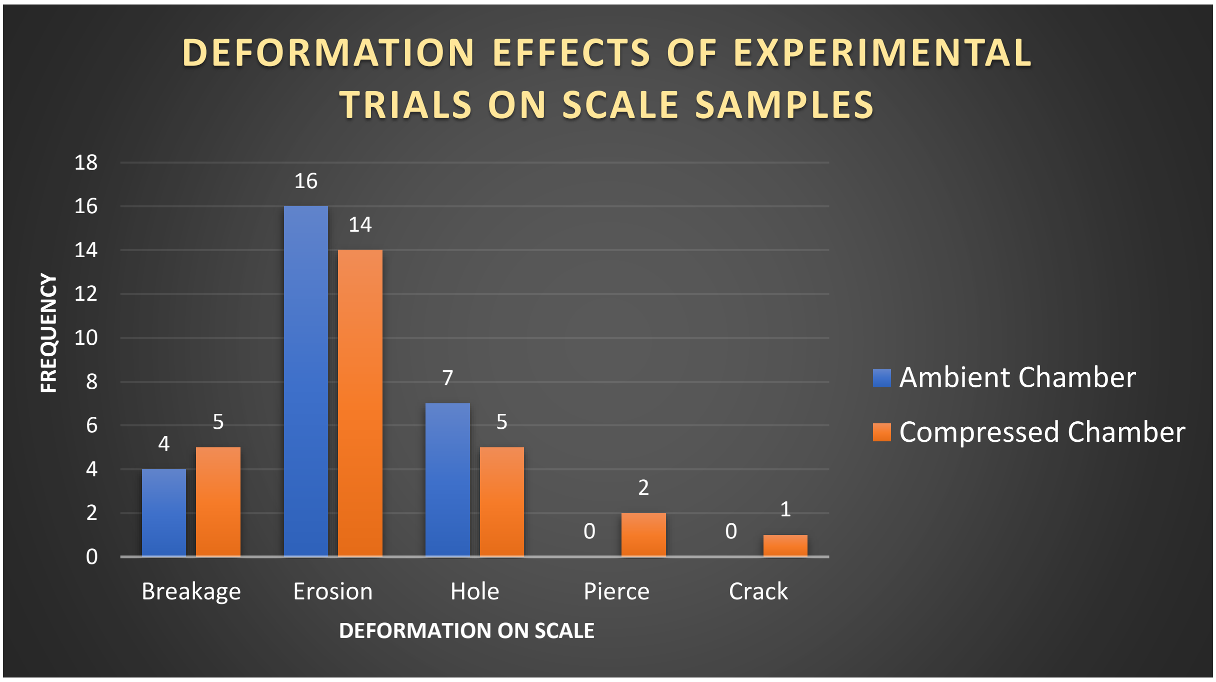



Figure 4.16: Comparison of Deformation Types Inflicted on Scale Samples at Ambient and Compressed Chamber Conditions

The deformations suffered by the scales (columns 13 of Table B2 and Table B3) have been classified into five, namely (in order of decreasing severity): (i) **breakage** when the scale sample is shattered, split into different separated parts or a huge chunk of it is chopped off; (ii) **crack** when the scale sample suffers vertical or horizontal cracks but still maintains its cylindrical shape; (iii) **pierce** when the scale sample has been perforated and the hole made cuts across its entire thickness; (iv) **hole** when internal bores are made on the scale sample such that the holes made do not extend across its entire thickness and; (v) **erosion** when only surface abrasions are made on the internal or external circumference of the scale sample.

In Figure 4.16, compressing the chamber was found to cause more of the first three severe deformation effects than the ambient chamber counterpart while the latter had more numbers of surface erosions and holes. This is attributable to the additional stress or fatigue on the scale sample and wave fluctuations created by the injection of compressed air into the chamber.

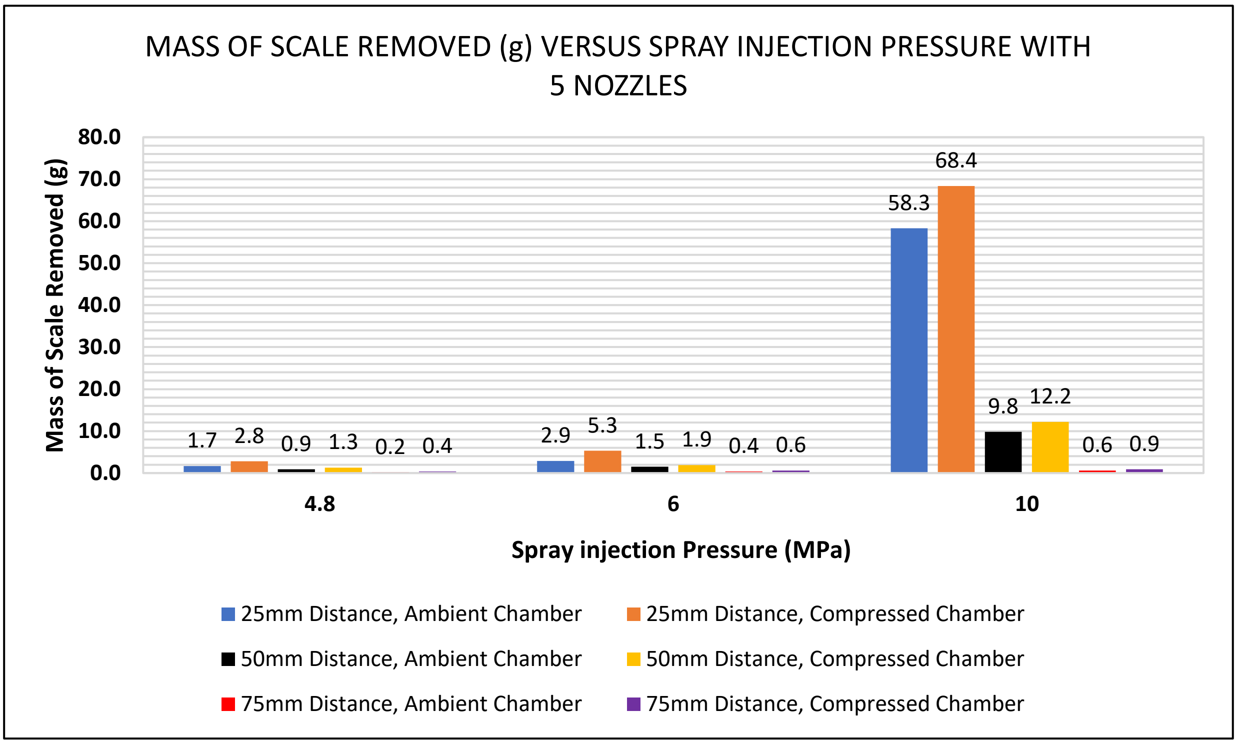



Figure 4.17: Comparison of Scale Removed under Ambient and Compressed Chamber Conditions with 5 Nozzles

In Figure 4.17, the avowal of higher scale removal at compressed chamber condition is further confirmed with the trend of a higher mass of scale removed at compressed chamber conditions relative to the ambient chamber conditions counterpart at all three pressures and 5 nozzles. At 10MPa for instance, an additional 10.1g of the scale was removed with the compressed chamber when sprayed at 25mm stand-off distance, at 50mm stand-off distance, an extra 2.4g of the scale was removed while an extra 0.3g was removed at 75mm stand-off distance. This pattern was consistent at lower numbers of nozzles, as shown in Figure 4.18 and Figure 4.19, with the highest incremental scale removal of 114.5g obtained with compressing the chamber and spraying at 6.0MPa injection pressure with 4 nozzles at 25mm spray distance.

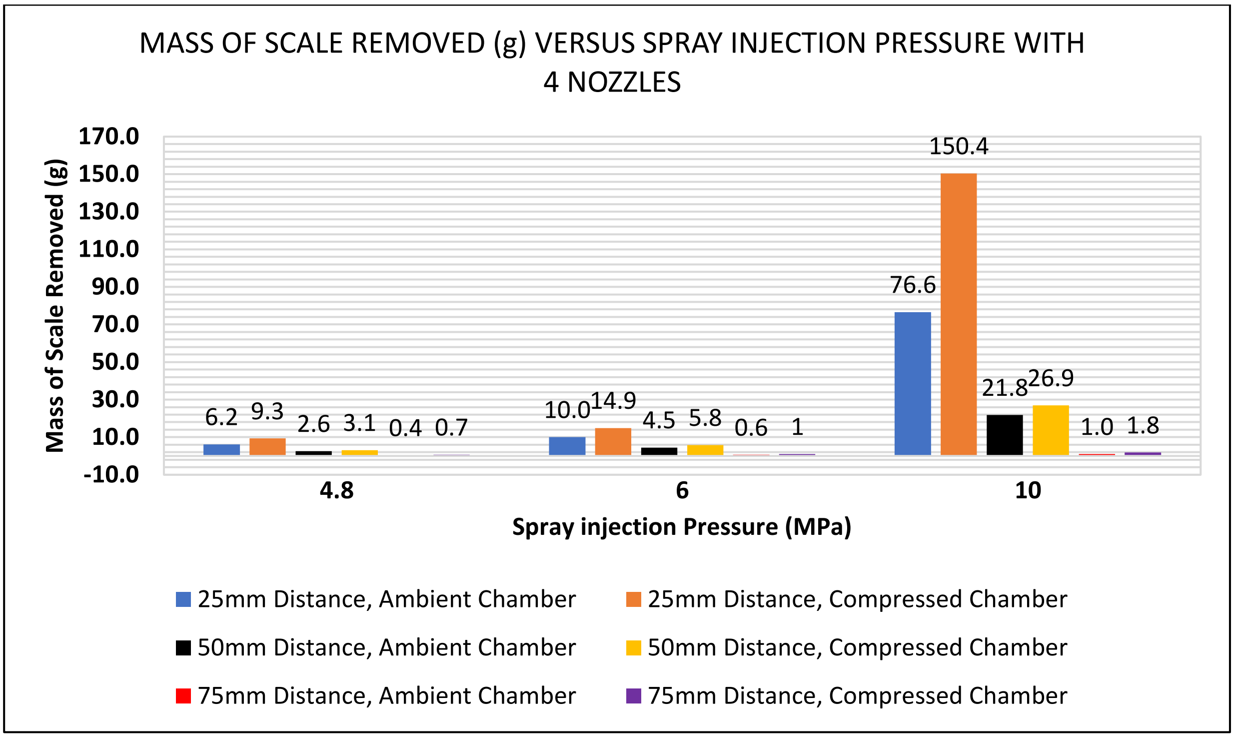



Figure 4.18: Comparison of Scale Removed under Ambient and Compressed Chamber Conditions with 4 Nozzles

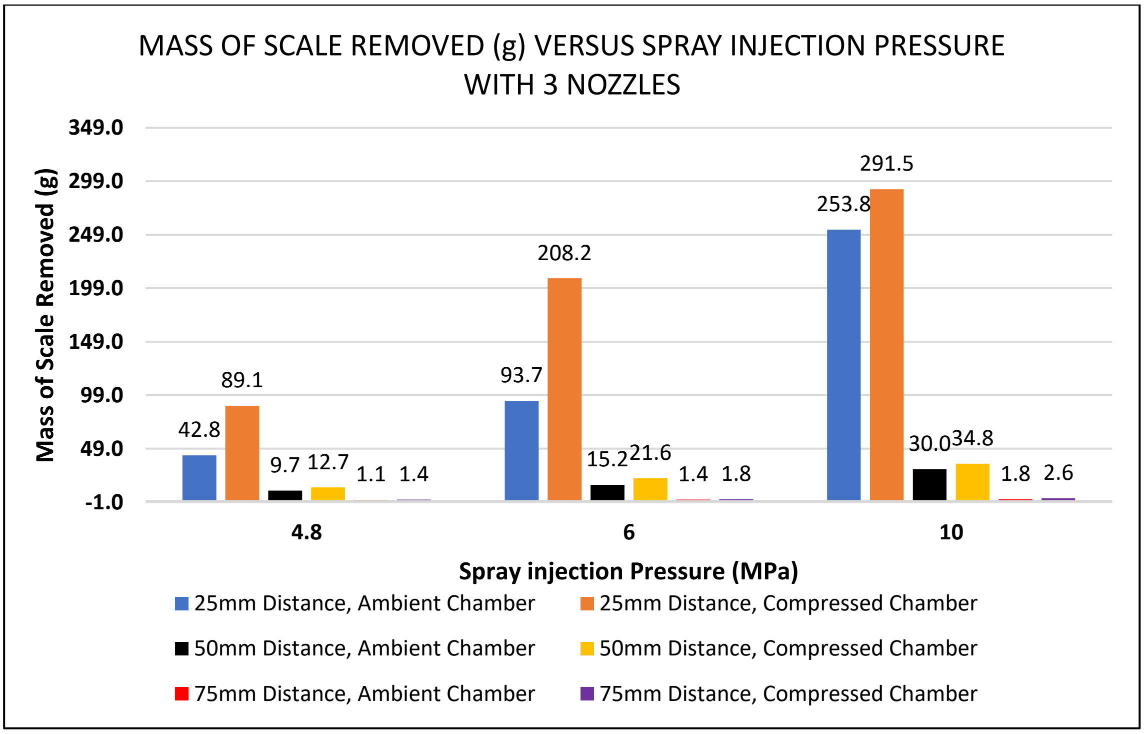



Figure 4.19: Comparison of Scale Removed under Ambient and Compressed Chamber Conditions with 3 Nozzles

# Chapter 5: Conclusion and Recommendation

## 5.1 Conclusions

The following conclusions have been derived from the results of this study:

- Scale samples were tested for how closely they represented oil field paraffin scales and good matches were obtained for their cooling behaviours with published cooling curves paraffin waxes.
- The rate of water injected was found to increase with an increase in the injection pressure and the number of nozzles because more atomizers or nozzles means less resistance to flow.
- The scale removal efficiency was observed to improve as the Spray distance or Stand-off distance reduces. This is because the spray particles exert more impact forces on the scales at shorter stand-off distances. In this work, reducing the spray distance from 75mm to 25mm caused an additional 57.7g of scale to be removed, a 96% increase in the scale removal efficiency and a progression from mere surface erosion of the scale sample to breaking it, when five flat-fan nozzles were utilized at 10MPa under ambient chamber condition. The trend was observed to be the same at the compressed chamber condition but a higher magnitude.
- For a given number of nozzles, the amount of scale removed was found to increase as the water injection pressure was increased because the more erosional effect was produced at high pressures due to the increase in mass flow rate with an increase in injection rate of water and consequent longer duration of contact of the HP water jets on the scales. However, as the stand-off distance increases, the effect of water injection pressure increment on scale removal was found to diminish due to the earlier established reason of reduced spray particle velocity and impact force at high stand-off distances.
- Comparing the use of a single flat-fan spray with multiple flat-fan sprays, the experiment revealed that additional scale removal can be as high as 248.5g when three nozzles are used at ambient chamber condition and 217.6g when the same number of nozzles are used at compressed descaling chamber condition. Exceptions to the increment were noticed when the scale was subjected to compressive forces at spray injection pressures of 4.8MPa and 6.0MPa at 25mm spray distance.
- Although scale removal with multiple nozzles recorded more increase than reduction, in the amount of scale removed relative to the use of single nozzles, it was found to decrease as the number of nozzles increases from three to five. This is because the higher number of nozzles create an increase in the effective, equivalent cross-sectional area of

flow through the jet nozzles and consequently decrease the exit velocity of the water particles from the nozzles. The implication of which is a reduced impact force on the scale.

- Subjecting the scale sample to compression caused more severe deformation effects on it when sprayed than spraying it at ambient chamber condition while the latter caused more erosions and holes on the scale samples because of the additional stress or fatigue exerted on it and wave fluctuations, around the scale sample, created by the injection of compressed air into the chamber during that phase of the experiment.
- The experiment revealed an additional 10.1g of the scale was removed with the compressed chamber condition, relative to the ambient chamber condition, when sprayed at 25mm stand-off distance; an extra 2.4g of scale when sprayed at 50mm stand-off distance; and an extra 0.3g when sprayed at 75mm stand-off distance at a spray injection pressure of 10MPa.
- An incremental scale removal of 114.5g was recorded with compressing the chamber and spraying at 6.0MPa injection pressure with 4 nozzles at 25mm stand-off distance.

## 5.2 Recommendations

- To better check fabricated scale samples representativeness of oil field soft scales, sample tests should not be limited to thermodynamic properties tests. Hardness tests and structural tests can also be used.
- To reduce differences in the properties of the scale samples, they should be produced in a single batch. Batch production can create variation in hardness and dryness of the scale samples and hence introduce errors in the experimental outcomes.
- For further works, numerical models of the rig can be developed with computational fluid dynamics and validated with the results of this experiment, then, used for more versatile investigations such as the effect of descaling at submerged condition and the removal of medium and hard scales.
- Finally, design analysis and optimization can be used to rank the factors that affect production tubing descaling, with HP flat-fan water jets, in order of their significance to enhance quick decision making on its usage for field workover operations.

# REFERENCES


Abbas, A. J. (2014). *Descaling of Petroleum Production Tubing utilising Aerated High-Pressure Flat Fan Water Sprays*. The University of Salford, Manchester.

Abbas, A. J, Nasr, G. G., Nourian, A. & Enyi, G. G. (2016). Impact Pressure Distribution in Flat Fan Nozzles for Descaling Oil Wells. *Journal of Energy and Power Engineering*, *10*(6). https://doi.org/10.17265/1934-8975/2016.06.003

Al-Arji, F. M., & Al-Amri, M. A. (2013). New Workflow for Scale Precipitation in Production Equipment Resulting from Formation and Injected Water Incompatibility: Field Case. https://doi.org/10.2118/167288-ms

Al-Dossary, M., Al-Driweesh, S., Al-Sagr, A. M., Bolarinwa, S., Haekal, M., & Noguera, J. A. (2014). Relaunch Coiled Tubing Foam Descaling in Depleted Sour Gas Well – Lessons Learned from Operation Failures. In *International Petroleum Technology Conference held in Kuala Lumpur, Malaysia, 10–12 December 2014. This* (pp. 1–11). Kuala Lumpur, Malaysia: Society of Petroleum Engineers. https://doi.org/10.2523/iptc-17881-ms

Anwar, M., & Abubakr, M. (2017). Innovation Technique and Successful Scale Removal Job With Coiled Tubing in Belayim Oil Field, Egypt: A Case History. In *Offshore Mediterranean Conference and Exhibition* (p. 6). Ravenna, Italy: Society of Petroleum Engineers. Retrieved from https://doi.org/

Aregbe, A. G. (2016). *Modeling and Prediction of Scale Formation in Petroleum Reservoir During Water MODELING AND PREDICTION OF SCALE FORMATION IN PETROLEUM RESERVOIRS DURING WATER INJECTION PROCESS*. The University of Lagos, Akoka, Yaba, Lagos, Nigeria. https://doi.org/10.13140/RG.2.1.4989.2726

Boer, R. B. De, Leerlooyer, K., Eigner, M. R. P., & A.R.D., B. van. (1995). Screening of Crude Oils for Asphalt Precipitation : Theory, Practice, and the Selection of Inhibitors. *SPE Production & Facilities*, (February), 55–61.

Borden, K. (2015). Flow Assurance: Hydrates and Paraffin Management. *Oil and Gas Facilities*, *3*(01), 29–33. https://doi.org/10.2118/0214-0029-ogf

Braun, G., & Boles, J. L. (2007). Characterization and Removal of Amorphous Aluminosilicate Scales. In *SPE Western Regional Meeting* (pp. 1–2). Bakersfield, California: Society of Petroleum Engineers. https://doi.org/10.2118/24068-ms

Brown, M. J., & Dobbs, J. B. (1998). A novel exothermic process for the removal of paraffin deposits in hydrocarbon production. In *NACE International Corrosion 98* (pp. 200–233). Houston, Texas: NACE International.

Chen, T., Wang, Q., Chang, F., & Albelharith, E. (2017). Multi-Functional and Non-Acidic Iron Sulfide Scale Dissolver for Downhole Applications. In *Abu Dhabi International Petroleum Exhibition and Conference Abu Dhabi, UAE, 13-16 November 2017* (pp. 1–11). Abu Dhabi, UAE: Shell Learning and Development. https://doi.org/10.2118/188924-ms

Chen, T., Wang, Q., Chang, F., & Albelharith, E. (2018). Paper No. 11081. In *NACE International Corrosion Conference and Expo 2018* (pp. 1–12).

Chen, T., Wang, Q., Chang, F., Aljeaban, N., & Aramco, S. (2019). IPTC-19315-MS Recent Development and Remaining Challenges of Iron Sulfide Scale Mitigation in Sour Gas Wells, 1–11.

Crabtree, M., Johnson, A., Eslinger, D., Fletcher, P., Miller, M., Johnson, A., & King, G. (1999). Fighting Scale — Removal and Prevention. *Oilfield Review*, 30–45. Retrieved from http://www.slb.com/~/media/Files/resources/oilfield_review/ors99/aut99/fighting.pdf

Denney, D. (2015). FeS-Scale Cleanout With High-Pressure Coiled Tubing and Tailored Fluid. *Journal of Petroleum Technology*, *66*(09), 154–156. https://doi.org/10.2118/0914-0154-jpt

EDGE. (2013). 100% Wax Cooling Curve and Melting Point. Retrieved May 21, 2019, from http://edge.rit.edu/edge/P13411/public/Wax Test Data

Elmorsey, S. A. (2013). Challenge and Successful Application for Scale Removal Gemsa Oil Field, Egypt: Field Study. In *SPE Middle East Oil and Gas Show and Conference* (pp. 1–7). Manama, Bahrain: Society of Petroleum Engineers. https://doi.org/10.2118/164274-ms

ENVIROFLUID. (2014). Removing Paraffin Wax Build-up from Oil Wells. Retrieved April 23, 2019, from https://envirofluid.com/articles/removing-paraffin-wax-build-up-from-oil-wells/

Enyi, G. C., Nasr, G. G., Nourian, A., El-Kamkhi, M. A., & Burby, M. L. (2012). Removal of Scales in Petroleum Production Tubing Utilising High-Pressure Atomisers. In *ICLASS 2012, 12th Triannual International Conference on Liquid Atomization and Spray Systems, Heidelberg, Germany, September 2-6, 2012* (pp. 1–9). Germany.

Franco, C. A., Solares, J. R., Al-Marri, H. M., Mukhles, A., Ramadhan, N. H., & Al-Saihati, A. H. (2010). Analysis of Deposition Mechanism of Mineral Scales Precipitating in the Sandface and Production Strings of Gas-Condensate Wells. *SPE Production & Operations*, *25*(02), 161–171. https://doi.org/10.2118/120410-pa

Fulford, R. S. (1975). Oilwell Paraffin Prevention Chemicals. *SPE Journal*, (5413), 171–177.

Guimaraes, Z., Almeida, V., Duque, L. H., Costa, G., Pinto, J. C., Chagas, J. V., … Alberto, C. (2008). Efficient Offshore Scale Removal Without a Rig: Planning, Logistics, and Execution, 1–7. https://doi.org/10.2118/113783-ms

Gupta, D. V. S., Szymczak, S., & Brown, M. (2009). Solid Production Chemicals Added with the Frac for Scale, Paraffin and Asphaltene Inhibition. In *SPE Hydraulic Fracturing Technology Conference* (pp. 1–5). The Woodlands, Texas, USA: Society of Petroleum Engineers. https://doi.org/10.2118/119393-ms

Hamdy, E., Abu Bakr, M., Abd El-Hay, A., Sisostris, S., Anwar, M., & El Farouk, O. (2014). Challenge and Successful Application for Scale Removal in Oil Field, Egypt: Field Study (pp. 1–7). Kuala Lumpur, Malaysia: International Petroleum Technology Conference. https://doi.org/10.2523/iptc-18139-ms

Hasan, A., Hejase, H., Abdelbaqi, S., Assi, A., & Hamdan, M. (2016). Comparative Effectiveness of Different Phase Change Materials to Improve Cooling Performance of Heat Sinks for Electronic Devices. *Applied Sciences*, *6*(9), 226. https://doi.org/10.3390/app6090226

Khormali, A., & Petrakov, D. G. (2016). Laboratory investigation of a new scale inhibitor for preventing calcium carbonate precipitation in oil reservoirs and production equipment. *Petroleum Science*, *13*(2), 320–327. https://doi.org/10.1007/s12182-016-0085-6

Mansoori, H., Mobedifard, V., & Kouhpeyma, A. M. (2017). Study Finds Simulation Flaws in Multiphase Environment. *Oil and Gas Journal*, *112*(November), 102–105.

McClaflin, G. G., & Whitfill, D. L. (2007). Control of Paraffin Deposition in Production Operations. *Journal of Petroleum Technology*, *36*(11), 1965–1970. https://doi.org/10.2118/12204-pa

Mirazizi, H. K., Shang, W., & Sarica, C. (2012). Experimental investigation of paraffin deposition under turbulent flow conditions. In *8th North American Conference on Multiphase Technology, 20-22 June, Banff, Alberta, Canada* (pp. 151-166. BHR-2012-A010).

Moghadasi, J., Jamialahmadi, M., Müller-Steinhagen, H., & Sharif, A. (2003). Scale Formation in Oil Reservoir and Production Equipment during Water Injection (Kinetics of CaSO4 and CaCO3 Crystal Growth and Effect on Formation Damage). In *SPE European Formation Damage Conference* (pp. 1–3). The Hague, Netherlands: Society of Petroleum Engineers. https://doi.org/10.2118/82233-ms

Moghadasi, J., Jamialahmadi, M., Müller-Steinhagen, H., Sharif, A., Ghalambor, A., Izadpanah, M. R., & Motaie, E. (2003). Scale Formation in Iranian Oil Reservoir and Production Equipment During Water Injection. In *International Symposium on Oilfield Scale* (pp. 1–4). Aberdeen, UK.: The Society of Petroleum Engineers. https://doi.org/10.2118/80406-MS

Mullins, O. C. (2005). Review of the Molecular Structure and Aggregation of Asphaltenes and Petroleomics. In *SSPE Annual Technical Conference and Exhibition* (p. 1). Dallas, Texas: Society of Petroleum Engineers. https://doi.org/10.2118/95801-pa

Nasr-El-Din, H., Al-Gamber, S., & Saiari, H. (2006). Field Application of Emulsified Scale Inhibitor Treatment To Mitigate Calcium Carbonate Scale in Horizontal Wells. In *SPE International Oilfield Scale Symposium held in Aberdeen, United Kingdom, 30 May–1 June 2006.* (pp. 2–9). Aberdeen, United Kingdom: Society of Petroleum Engineers. https://doi.org/10.2523/100456-ms

Nejad, A. M., & Karimi, M. S. (2017). Investigation Of The Influence Of Scaling On Corrosion Behavior Of Tubing In Oil Wells. *INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH*, *6*, 5. Retrieved from www.ijstr.org

Peng, Y., & Guo, Z. (2017). On the Sweet Corrosion of Oil and Gas Wells. *International Journal of Science and Engineering Investigations*, *6*. Retrieved from www.IJSEI.com

Ramones, M., Rachid, R., Flor, D., Gutierrez, L., & Milne, A. (2015). Removal of Organic and Inorganic Scale from Electric Submersible Pumps. In *SPE Artificial Lift Conference — Latin America and the Caribbean held* (pp. 27–28). Salvador, Bahia: Society of Petroleum Engineers. https://doi.org/10.2118/173928-ms

RIGZONE. (n.d.). US Geological Survey Heavy Oil Statistics Map. Retrieved April 23, 2019, from https://www.rigzone.com/training/heavyoil/images/map_HeavyOil_Stats.gif

Sanjay, M., Simanta, B., & Kulwant, S. (2007). Paraffin Problems in Crude Oil Production And Transportation: A Review. *SPE Production & Facilities*, *10*(01), 50–54. https://doi.org/10.2118/28181-pa

Sutton, G. D. (2007). Aqueous Systems for Paraffin Removal. In *AIME Symposium on Formation Damage Control.* (pp. 1–6). Houston, Texas: Society of Petroleum Engineers. https://doi.org/10.2118/5704-ms

Theyab, M. A. (2017). Study of Fluid Flow Assurance in Hydrocarbon Production-Investigation Wax Mechanisms. London South Bank University. Retrieved from http://researchopen.lsbu.ac.uk/1855/1/2017_PhD_Al_Theyab.pdf

Thomas, D. C. (1988). Selection of Paraffin Control Products and Applications. In *SPE International Meeting on Petroleum Engineering* (pp. 1–9). Tianjin, China: Society of Petroleum Engineers.

Turbakov, M. S., & Riabokon, E. P. (2014). Improving of Cleaning Efficiency of Oil Pipeline From Paraffin (Russian). In *SPE Russian Oil and Gas Technical Conference and Exhibition* (pp. 1–9). Moscow, Russia: Society of Petroleum Engineers. https://doi.org/10.2118/171295-ru

Vazirian, M., Charpentier, T. V. J., Penna, M. de O., & Neville1, A. (2015). Surface Inorganic Scale Formation in Oil and Gas Industry: as Adhesion and Deposition Processes. *Journal of Petroleum Science and Engineering*, *137.*, 22-32. https://doi.org/10.1016/j.petrol.2015.11.005

Wang, Q., Chen, T., Chang, F., Al-Nasser Saudi Aramco Dhahran, W., Arabia, S., & Liang, F. (2018). Searching for Iron Sulfide Scale Dissolver for Downhole Applications. *NACE International*, (10545), 1–10. Retrieved from https://www.onepetro.org/download/conference-paper/NACE-2018-10545?id=conference-paper%2FNACE-2018-10545

Wang, Q., Chen, T., Chang, F. F., Nasser, W. Al, Shen, S., Al-Badairy, H., … Al-Mukhles, A. (2017). Iron Sulfide Scale Dissolver for Downhole Application: Where Are We Now? In *SPE International Conference on Oilfield Chemistry held in Montgomery, Texas, USA, 3–5 April 2017.* (p. 1). Montgomery, Texas, USA, Society of Petroleum Engineers. https://doi.org/10.2118/184513-ms

Wang, Q., Leal, J., Syafii, I., Mukhles, A. E., Chen, T., Chang, F., & Espinosa, M. (2016). Iron Sulfide and Removal in Scale Formation Sour Gas Wells. In *SPE International Oilfield Scale Conference and Exhibition held in Aberdeen, Scotland, UK, 11–12 May 2016* (pp. 1–26). Aberdeen, Scotland, UK, 11–12: Society of Petroleum Engineers. https://doi.org/10.2118/179869-ms

# Appendices

## Appendix A: Tabulation of Results

Table A4: RESULTS OF RIG CALIBRATION

| Number of Nozzles | Mass flow rate | Injection Pressure (bar) | | |
|---|---|---|---|---|
| | | RIG | Pump Gauge | Control Board |
| | (kg/sec) | bar | bar | bar |
| 5 | 0.434 | 48 | 100 | 58 |
| | 0.462 | 60 | 120 | 75 |
| | 0.765 | 100 | 190 | 150 |
| 4 | 0.377 | 48 | 90 | 60 |
| | 0.411 | 60 | 100 | 75 |
| | 0.608 | 100 | 165 | 135 |
| 3 | 0.313 | 48 | 40 | 50 |
| | 0.306 | 60 | 55 | 70 |
| | 0.353 | 100 | 140 | 120 |

TABLE A5: EXPERIMENTAL OUTCOME OF DESCALING TRIALS UNDER AMBIENT CHAMBER CONDITION

| Run no. | No. of nozzles | Chamber Condition (0.1MPa) | Mass flow rate (kg/s) | Injection pressure (MPa) | Nozzle Config. | Stand-off distance (mm) | Scale ID | Mass of scale Before (kg) | Mass of scale after (Kg) | Mass of scale removed (Kg) | Descaling time (S) | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5 | Ambient | 0.434 | 4.8 | Pentagon | 25 | 17-SH | 0.5731 | 0.5714 | 0.0017 | 180 | Eroded |
| 2 | | | | | | 50 | 25SH | 0.5209 | 0.52 | 0.0009 | 180 | Eroded |
| 3 | | | | | | 75 | 44SH | 0.5606 | 0.5604 | 0.0002 | 180 | Eroded |
| 4 | | | 0.462 | 6 | Pentagon | 25 | 5SH | 0.5749 | 0.572 | 0.0029 | 180 | Eroded |
| 5 | | | | | | 50 | 73SH | 0.5947 | 0.5932 | 0.0015 | 180 | Eroded |
| 6 | | | | | | 75 | 40SH | 0.5693 | 0.5689 | 0.0004 | 180 | Eroded |
| 7 | | | 0.765 | 10 | Pentagon | 25 | 11- SH | 0.5689 | 0.5106 | 0.0583 | 180 | Broken |
| 8 | | | | | | 50 | 65SH | 0.5337 | 0.5239 | 0.0098 | 180 | Eroded |
| 9 | | | | | | 75 | 42SH | 0.573 | 0.5724 | 0.0006 | 180 | Eroded |
| 10 | 4 | Ambient | 0.377 | 4.8 | Rectangle | 25 | 38SH | 0.5427 | 0.5365 | 0.0062 | 180 | Hole |
| 11 | | | | | | 50 | 3SH | 0.5448 | 0.5422 | 0.0026 | 180 | Eroded |
| 12 | | | | | | 75 | 58SH | 0.5411 | 0.5407 | 0.0004 | 180 | Eroded |
| 13 | | | 0.411 | 6 | Rectangle | 25 | 8- SH | 0.5321 | 0.5221 | 0.01 | 180 | Hole |
| 14 | | | | | | 50 | 59SH | 0.5619 | 0.5574 | 0.0045 | 180 | Eroded |
| 15 | | | | | | 75 | 47SH | 0.5752 | 0.5746 | 0.0006 | 180 | Eroded |
| 16 | | | 0.608 | 10 | Rectangle | 25 | 10- SH | 0.5236 | 0.447 | 0.0766 | 180 | Broken |
| 17 | | | | | | 50 | 70SH | 0.5519 | 0.5301 | 0.0218 | 180 | Hole |
| 18 | | | | | | 75 | 49SH | 0.5509 | 0.5499 | 0.001 | 180 | Eroded |
| 19 | 3 | Ambient | 0.313 | 4.8 | Triangle | 25 | 4SH | 0.5809 | 0.5381 | 0.0428 | 180 | Hole |
| 20 | | | | | | 50 | 34SH | 0.5511 | 0.5414 | 0.0097 | 180 | Hole |
| 21 | | | | | | 75 | 45SH | 0.5694 | 0.5683 | 0.0011 | 180 | Eroded |
| 22 | | | 0.306 | 6 | Triangle | 25 | 15- SH | 0.6597 | 0.566 | 0.0937 | 180 | Broken |
| 23 | | | | | | 50 | 29SH | 0.5577 | 0.5425 | 0.0152 | 180 | Hole |
| 24 | | | | | | 75 | 52SH | 0.5809 | 0.5795 | 0.0014 | 180 | Eroded |
| 25 | | | 0.353 | 10 | Triangle | 25 | 21-SH | 0.5177 | 0.2639 | 0.2538 | 180 | Broken |
| 26 | | | | | | 50 | 67SH | 0.519 | 0.489 | 0.03 | 180 | Hole |
| 27 | | | | | | 75 | 51SH | 0.5805 | 0.5787 | 0.0018 | 180 | Eroded |

TABLE A6: EXPERIMENTAL OUTCOME OF DESCALING TRIALS UNDER COMPRESSED CHAMBER CONDITION

| Run no. | No. of nozzles | Chamber Condition (0.2MPa) | Mass flow rate (kg/s) | Injection pressure (MPa) | Nozzle Config. | Stand-off distance (mm) | Scale ID | Mass of scale Before (kg) | Mass of scale after (Kg) | Mass of scale removed (Kg) | Descaling time (S) | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5 | Compressed | 0.434 | 4.8 | Pentagon | 25 | 21SHA | 0.5559 | 0.5531 | 0.0028 | 180 | Eroded |
| 2 | | | | | | 50 | 4-SHA | 0.5714 | 0.5701 | 0.0013 | 180 | Eroded |
| 3 | | | | | | 75 | 69SHA | 0.5627 | 0.5623 | 0.0004 | 180 | Eroded |
| 4 | | | 0.462 | 6 | Pentagon | 25 | 55SHA | 0.5193 | 0.514 | 0.0053 | 180 | Hole |
| 5 | | | | | | 50 | 65SHA | 0.5739 | 0.572 | 0.0019 | 180 | Eroded |
| 6 | | | | | | 75 | 5-SHA | 0.5447 | 0.5441 | 0.0006 | 180 | Eroded |
| 7 | | | 0.765 | 10 | Pentagon | 25 | 38SHA | 0.5291 | 0.4607 | 0.0684 | 180 | Broken |
| 8 | | | | | | 50 | 27SHA | 0.5283 | 0.5161 | 0.0122 | 180 | Hole |
| 9 | | | | | | 75 | 44SHA | 0.5973 | 0.5964 | 0.0009 | 180 | Eroded |
| 10 | 4 | Compressed | 0.377 | 4.8 | Rectangle | 25 | 11-SHA | 0.5713 | 0.562 | 0.0093 | 180 | Hole |
| 11 | | | | | | 50 | 25SHA | 0.5375 | 0.5344 | 0.0031 | 180 | Eroded |
| 12 | | | | | | 75 | 46SHA | 0.5198 | 0.5191 | 0.0007 | 180 | Eroded |
| 13 | | | 0.411 | 6 | Rectangle | 25 | 7-SHA | 0.51 | 0.4951 | 0.0149 | 180 | Broken |
| 14 | | | | | | 50 | 67SHA | 0.5173 | 0.5115 | 0.0058 | 180 | Eroded |
| 15 | | | | | | 75 | 52SHA | 0.5672 | 0.5662 | 0.001 | 180 | Eroded |
| 16 | | | 0.608 | 10 | Rectangle | 25 | 12-SHA | 0.5855 | 0.4351 | 0.1504 | 180 | Broken |
| 17 | | | | | | 50 | 28SHA | 0.5761 | 0.5492 | 0.0269 | 180 | Cracked |
| 18 | | | | | | 75 | 48SHA | 0.5535 | 0.5517 | 0.0018 | 180 | Eroded |
| 19 | 3 | Compressed | 0.313 | 4.8 | Triangle | 25 | 29SHA | 0.5717 | 0.4826 | 0.0891 | 180 | Perforated |
| 20 | | | | | | 50 | 34SHA | 0.5659 | 0.5532 | 0.0127 | 180 | Hole |
| 21 | | | | | | 75 | 51SHA | 0.5543 | 0.5529 | 0.0014 | 180 | Eroded |
| 22 | | | 0.306 | 6 | Triangle | 25 | 13-SHA | 0.5316 | 0.3234 | 0.2082 | 180 | Broken |
| 23 | | | | | | 50 | 76SHA | 0.5297 | 0.5081 | 0.0216 | 180 | Hole |
| 24 | | | | | | 75 | 81SHA | 0.5487 | 0.5469 | 0.0018 | 180 | Eroded |
| 25 | | | 0.353 | 10 | Triangle | 25 | 24SHA | 0.5648 | 0.2733 | 0.2915 | 180 | Broken |
| 26 | | | | | | 50 | 36SHA | 0.5837 | 0.5489 | 0.0348 | 180 | Pierced |
| 27 | | | | | | 75 | 79SHA | 0.57 | 0.5674 | 0.0026 | 180 | Eroded |

# Appendix B: Qualitative Results Presentation

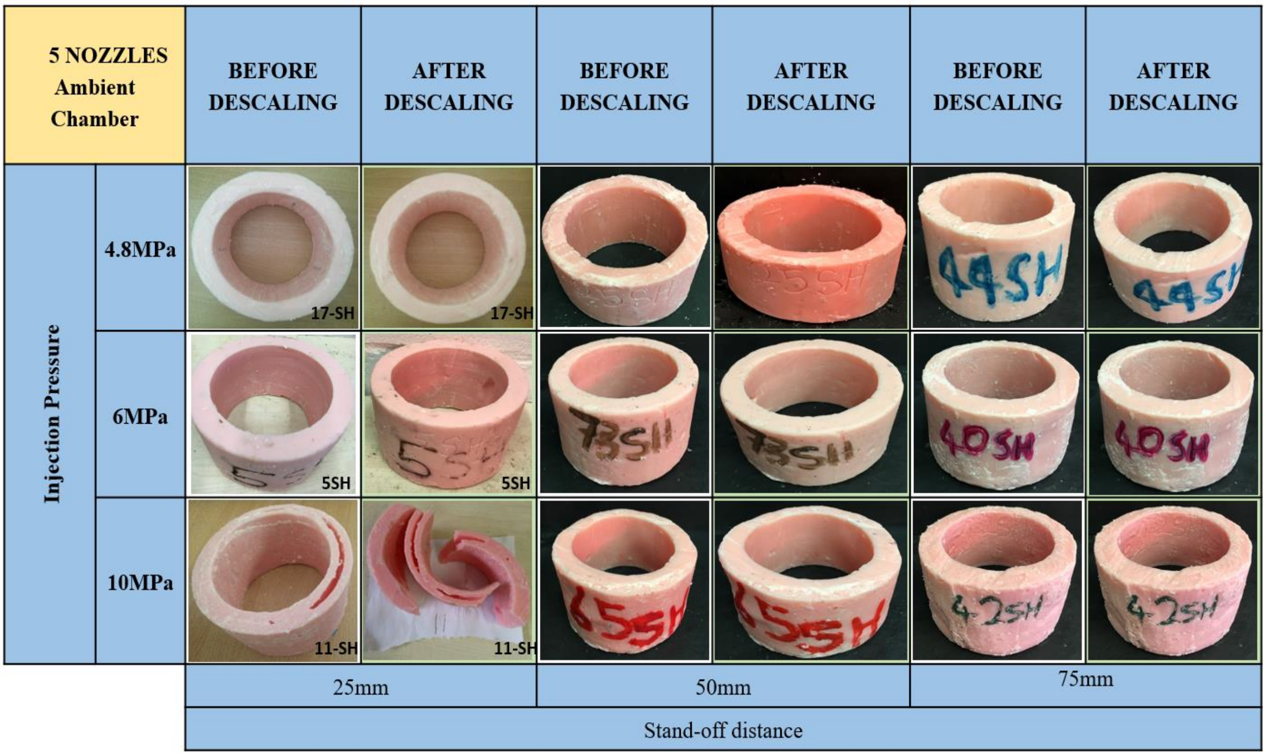



Figure B1: Pictures of Scale Samples Before and After Experimental Trials for 5 Nozzles at Ambient Chamber Condition

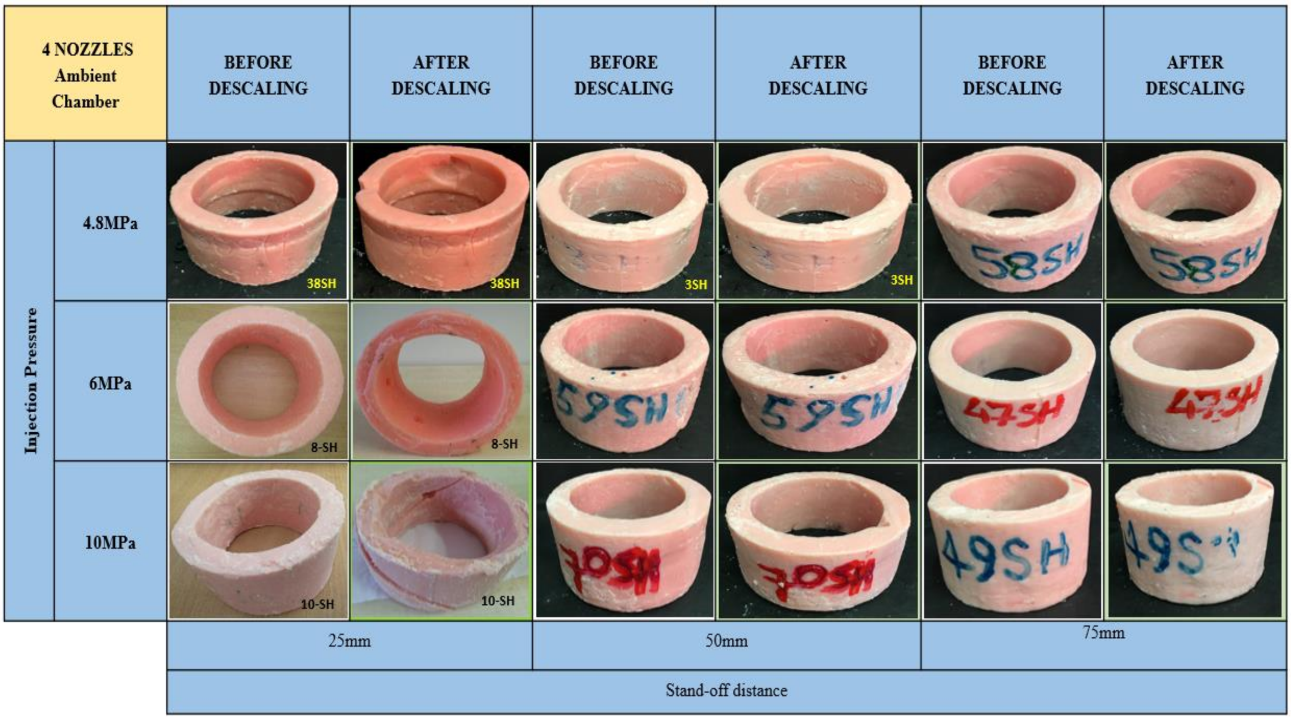



Figure B2: Pictures of Scale Samples Before and After Experimental Trials for 4 Nozzles at Ambient Chamber Condition

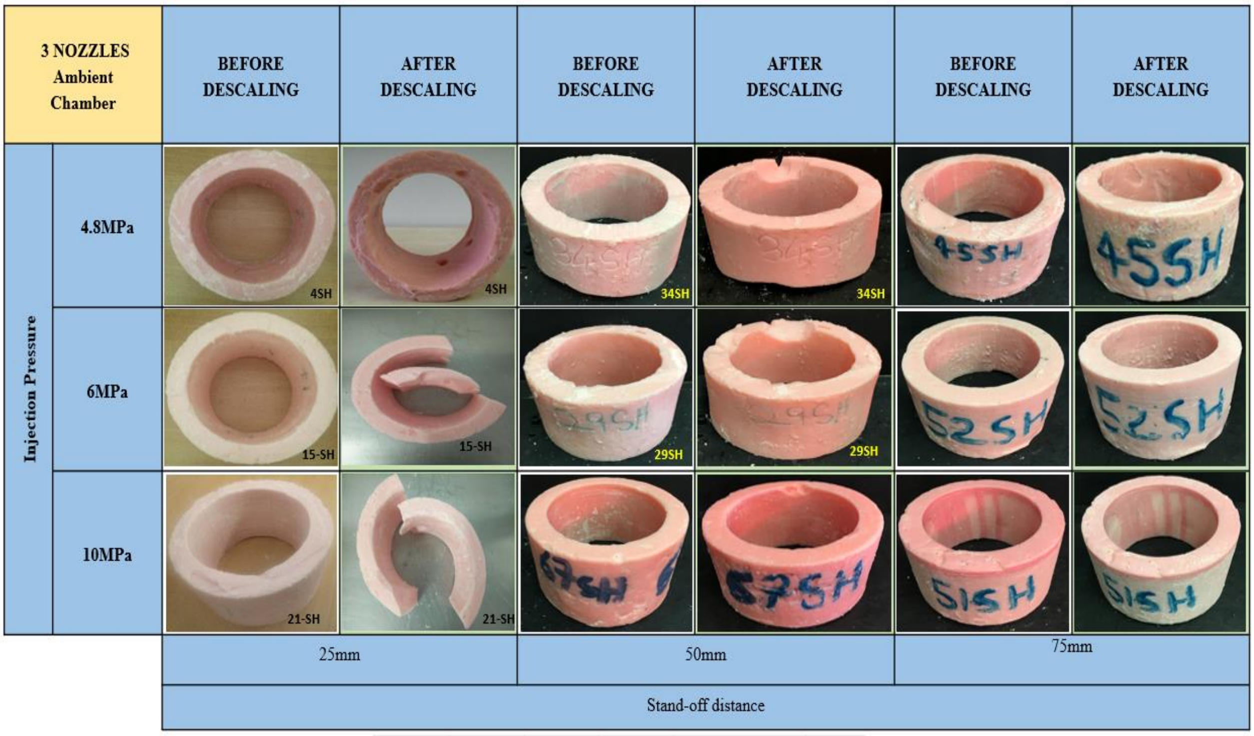



Figure B3: Pictures of Scale Samples Before and After Experimental Trials for 3 Nozzles at Ambient Chamber Condition


Figure B4: Pictures of Scale Samples Before and After Experimental Trials for 5 Nozzles at Compressed Chamber Condition

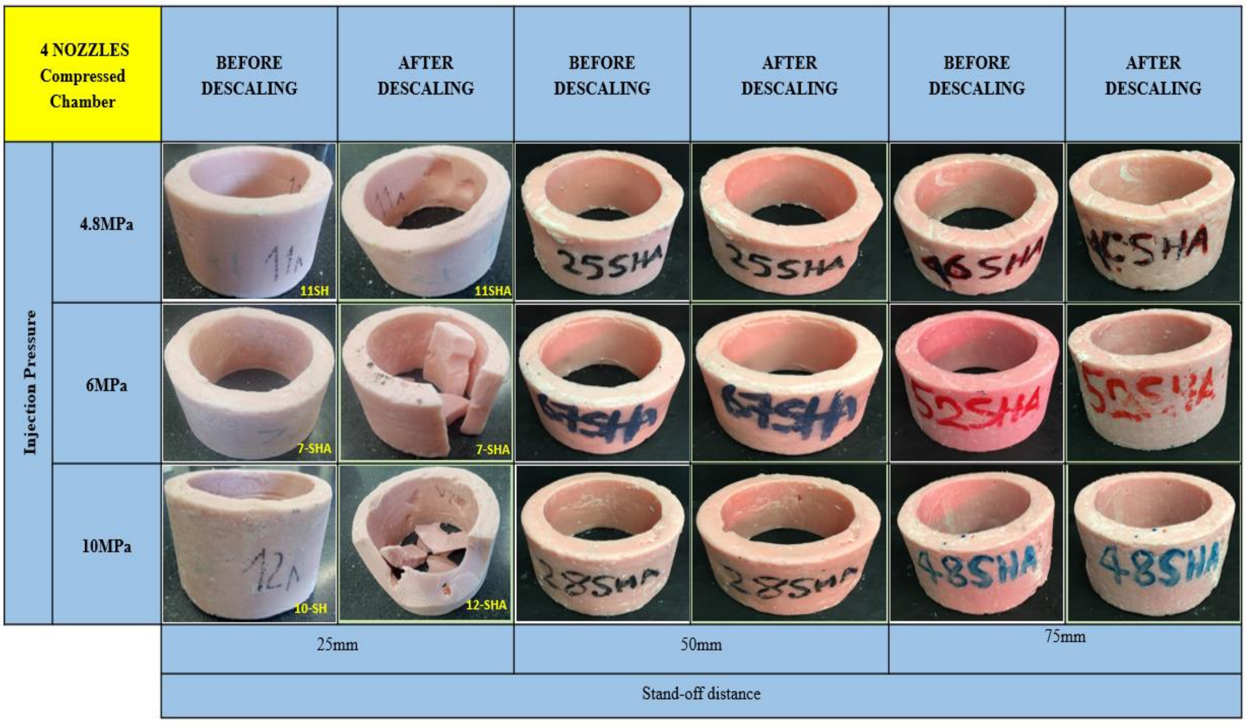



Figure B5: Pictures of Scale Samples Before and After Experimental Trials for 4 Nozzles at Compressed Chamber Condition


Figure B6: Pictures of Scale Samples Before and After Experimental Trials for 3 Nozzles at Compressed Chamber Condition

# Appendix C: Spray Characterisation

## 09 Nozzles & washing accessories

### Further information about high pressure nozzles

Output in l/min depends on pressure in bar

| D | Ø* | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 | 160 | 175 | 200 | 225 | 250 | 300 | 400 | 500 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 02 | 1,00 | 2,5 | 2,8 | 3,2 | 3,5 | 3,7 | 4,0 | 4,2 | 4,5 | 4,7 | 4,8 | 5,0 | 5,3 | 5,4 | 5,6 | 5,9 | 6,3 | 6,7 | 7,0 | 7,7 | 8,9 | 9,9 |
| 025 | 1,10 | 3,1 | 3,5 | 4,0 | 4,3 | 4,7 | 5,0 | 5,3 | 5,6 | 5,9 | 6,1 | 6,4 | 6,6 | 6,9 | 7,1 | 7,5 | 8,0 | 8,5 | 9,0 | 9,9 | 11,4 | 12,7 |
| 03 | 1,18 | 3,7 | 4,3 | 4,8 | 5,3 | 5,7 | 6,1 | 6,3 | 6,8 | 7,1 | 7,4 | 7,7 | 8,0 | 8,3 | 8,6 | 9,0 | 9,6 | 10,2 | 10,7 | 11,8 | 13,5 | 15,1 |
| 035 | 1,30 | 4,2 | 4,9 | 5,5 | 6,0 | 6,5 | 7,0 | 7,4 | 7,8 | 8,2 | 8,6 | 8,9 | 9,2 | 9,5 | 9,8 | 10,3 | 11,0 | 11,7 | 12,3 | 13,8 | 15,5 | 17,8 |
| 04 | 1,35 | 5,2 | 5,9 | 6,6 | 7,3 | 7,8 | 8,4 | 8,9 | 9,4 | 9,8 | 10,3 | 10,7 | 11,1 | 11,5 | 11,9 | 12,4 | 13,3 | 14,1 | 14,8 | 16,3 | 18,7 | 20,9 |
| 045 | 1,40 | 5,5 | 6,4 | 7,1 | 7,8 | 8,4 | 9,0 | 9,6 | 10,2 | 10,5 | 10,9 | 11,4 | 11,8 | 12,2 | 12,6 | 13,2 | 14,1 | 15,0 | 15,8 | 17,4 | 19,9 | 22,3 |
| 05 | 1,55 | 6,2 | 7,1 | 8,0 | 8,7 | 9,4 | 10,0 | 10,7 | 11,3 | 11,8 | 12,4 | 12,9 | 13,4 | 13,8 | 14,3 | 14,9 | 16,0 | 16,9 | 17,9 | 19,7 | 22,6 | 25,3 |
| 055 | 1,60 | 6,8 | 7,8 | 8,7 | 9,6 | 10,3 | 11,1 | 11,8 | 12,4 | 13,0 | 13,6 | 14,1 | 14,7 | 15,2 | 15,7 | 16,4 | 17,5 | 18,6 | 19,6 | 21,7 | 25,0 | 28,0 |
| 06 | 1,72 | 7,4 | 8,6 | 9,6 | 10,4 | 11,3 | 12,1 | 12,8 | 13,6 | 14,3 | 14,9 | 15,5 | 16,0 | 16,7 | 17,2 | 18,0 | 19,2 | 20,4 | 21,5 | 23,7 | 27,1 | 30,3 |
| 065 | 1,75 | 8,0 | 9,3 | 10,4 | 11,3 | 12,3 | 13,2 | 14,0 | 14,7 | 15,4 | 16,1 | 16,8 | 17,4 | 18,0 | 18,6 | 19,4 | 20,8 | 22,0 | 23,2 | 25,6 | 29,3 | 32,7 |
| 07 | 1,80 | 8,6 | 10,0 | 11,2 | 12,2 | 13,2 | 14,1 | 15,0 | 15,8 | 16,6 | 17,3 | 18,0 | 18,7 | 19,3 | 20,0 | 20,9 | 22,3 | 23,7 | 25,0 | 27,1 | 31,3 | 35,0 |
| 075 | 1,90 | 9,3 | 10,7 | 12,0 | 13,1 | 14,2 | 15,2 | 16,1 | 16,9 | 17,7 | 18,5 | 19,3 | 20,0 | 20,7 | 21,4 | 22,4 | 23,9 | 25,3 | 26,7 | 29,4 | 33,7 | 37,7 |
| 08 | 2,05 | 9,8 | 11,3 | 12,7 | 14,0 | 15,1 | 16,1 | 17,1 | 18,0 | 18,9 | 19,7 | 20,5 | 21,3 | 22,0 | 22,8 | 23,8 | 25,5 | 27,0 | 28,5 | 31,4 | 35,9 | 40,2 |
| 085 | 2,08 | 10,4 | 12,1 | 13,5 | 14,8 | 16,0 | 17,1 | 18,1 | 19,1 | 20,0 | 20,9 | 21,8 | 22,6 | 23,4 | 24,1 | 25,3 | 27,0 | 28,6 | 30,2 | 34,5 | 39,8 | 44,5 |
| 09 | 2,10 | 11,1 | 12,8 | 14,3 | 15,7 | 17,0 | 18,0 | 19,2 | 20,2 | 21,2 | 22,1 | 23,0 | 23,9 | 24,7 | 25,5 | 26,7 | 28,6 | 30,3 | 31,9 | 35,1 | 40,2 | 45,0 |
| 10 | 2,30 | 12,3 | 14,2 | 16,0 | 17,4 | 18,9 | 20,1 | 21,4 | 22,5 | 23,6 | 24,6 | 25,6 | 26,6 | 27,6 | 28,5 | 29,8 | 31,8 | 33,7 | 35,6 | 39,2 | 44,9 | 50,2 |
| 11 | 2,42 | 13,4 | 15,5 | 17,3 | 19,0 | 20,5 | 22,0 | 23,3 | 24,5 | 25,7 | 26,9 | 28,0 | 29,1 | 30,1 | 31,1 | 32,5 | 34,7 | 36,8 | 38,8 | 43,4 | 50,1 | 56,0 |
| 12 | 2,50 | 14,6 | 16,9 | 18,9 | 20,8 | 22,4 | 24,0 | 25,4 | 26,8 | 28,1 | 29,4 | 30,6 | 31,7 | 32,8 | 33,9 | 35,4 | 37,9 | 40,2 | 42,4 | 46,7 | 53,4 | 59,8 |
| 13 | 2,55 | 15,9 | 18,3 | 20,5 | 22,5 | 24,3 | 26,0 | 27,5 | 29,0 | 30,4 | 31,8 | 33,1 | 34,4 | 35,6 | 36,7 | 38,4 | 41,1 | 43,6 | 45,9 | 50,5 | 57,8 | 64,7 |
| 14 | 2,60 | 17,1 | 19,7 | 22,1 | 24,2 | 26,1 | 28,0 | 29,6 | 31,3 | 32,8 | 34,2 | 35,6 | 37,0 | 38,3 | 39,5 | 41,4 | 44,3 | 46,9 | 49,4 | 55,0 | 63,5 | 71,0 |
| 15 | 2,70 | 18,5 | 21,3 | 23,9 | 26,1 | 28,3 | 30,2 | 32,1 | 33,8 | 35,3 | 36,9 | 38,4 | 39,9 | 41,3 | 42,6 | 44,6 | 47,7 | 50,6 | 53,3 | 58,7 | 67,2 | 75,2 |
| 20 | 3,05 | 24,7 | 28,5 | 31,9 | 34,9 | 37,8 | 40,3 | 42,7 | 45,1 | 47,2 | 49,3 | 51,3 | 53,2 | 55,1 | 56,9 | 59,5 | 63,6 | 67,5 | 71,1 | 78,2 | 89,6 | 100,0 |
| 30 | 3,90 | 37,0 | 42,7 | 47,8 | 52,4 | 56,6 | 60,5 | 64,2 | 67,6 | 70,9 | 74,0 | 77,1 | 80,0 | 82,8 | 85,5 | 89,4 | 95,6 | 101,0 | 107,0 | 118,0 | 149,0 | 151,0 |
| 40 | 4,20 | 49,4 | 57,0 | 63,7 | 69,8 | 75,4 | 80,7 | 85,5 | 90,2 | 94,6 | 98,8 | 103,0 | 107,0 | 110,0 | 114,0 | 119,0 | 127,0 | 135,0 | 143,0 | 157,0 | 198,0 | 202,0 |

Please find table which shows flow rates and pressures associated with nozzle size.

Your Lechler nozzle is a 2505 = 25° angle
05 orifice

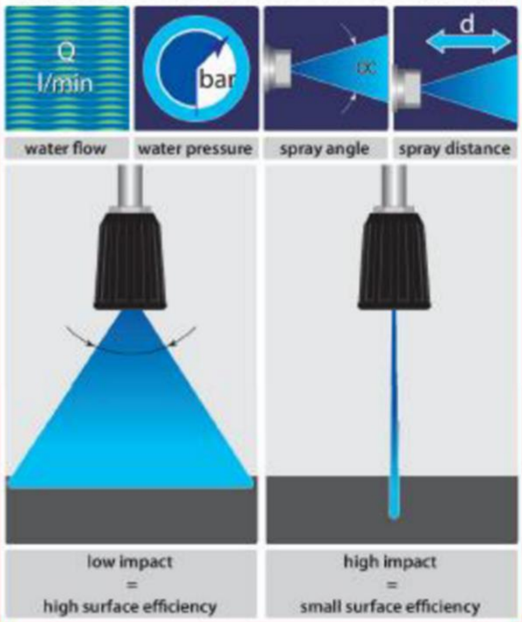
For flow rates - read the pressure (bar) along the top and follow it down to the marked box and this will show you your flow (lpm)

Please use the below formula to calculate the nozzle size required if you know your flow rate and pump pressure

$$\text{Nozzle Size} = \sqrt{\frac{20}{\text{Bar}}} \times \text{flow (lpm)}$$

I hope this helps

Important for excellent high pressure cleaning is the impact of the spray jet which is made up of 4 features.




Symbols D nozzle ⟷ flow Ø diameter

178

Figure C1: Flat-fan Atomizer Chart

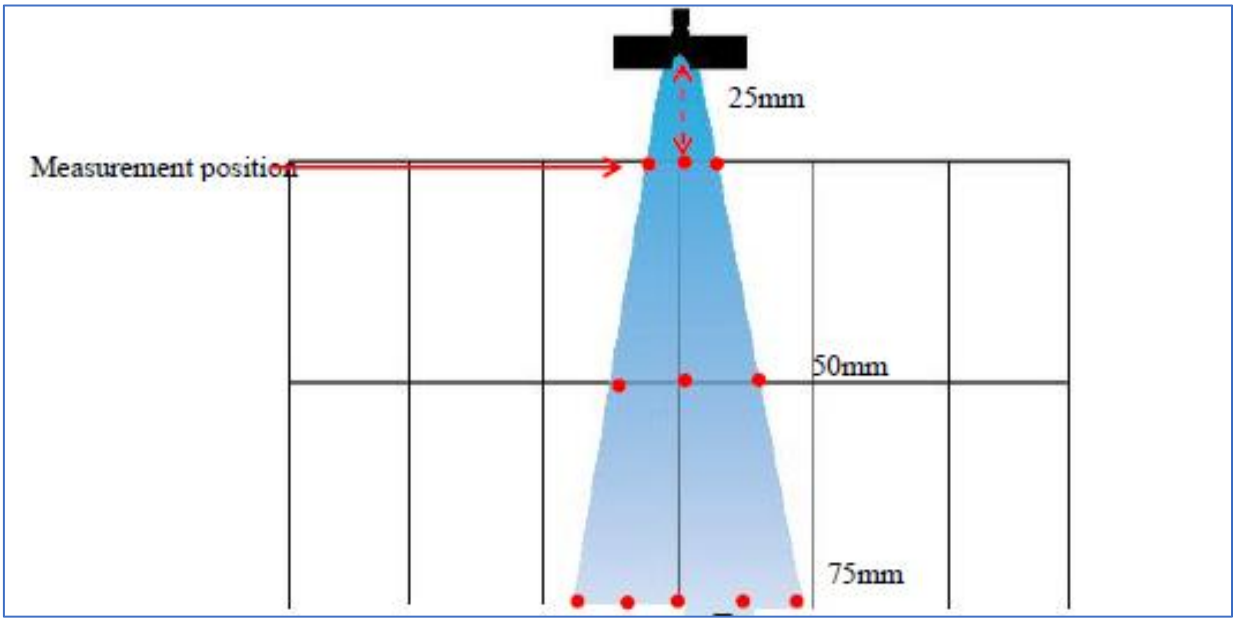


Figure C2: Abbas Impact Pressure Grid of the Spray Droplets

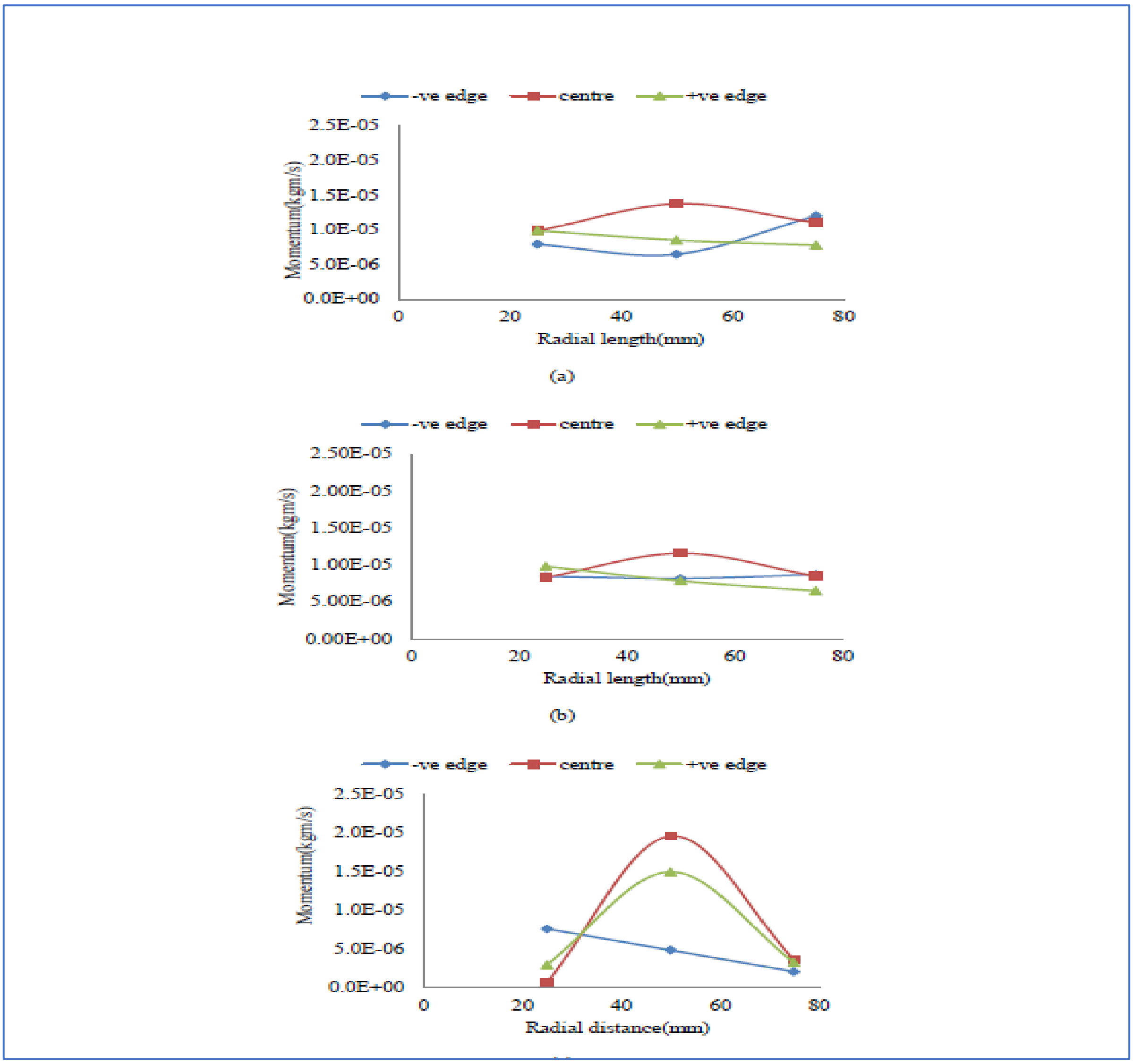


Figure C3: (Abbas, 2014) Spray Droplet Momentum at Various Positions