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IMPROVING THE FLOWABILITY OF HEAVY CRUDE OIL IN PIPELINES USING PREPARED NANOSILICA: EXPERIMENTAL INVESTIGATION AND CFD SIMULATION

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Abstract

One of the economic important challenges in oil pipeline transportation is to keep the flowability and reduce the pressure drop along the pipe. In this work, the flowability of Iraqi crude oil in the pipe is enhanced using nanotechnology. A locally prepared nano silica is used for this purpose with different concentrations (50, 100, 150, 200, 300, 400, 500,600, and 700) ppm. The experiments are carried out using horizontal stainless-steel pipe of 4 m length and 4.5 cm inside diameter. The results show that nano silica is effectively reduced the pressure drop and crude oil viscosity; also, this reduction increases with increasing the particle concentration up to the optimum value of 100 ppm at which maximum reduction in pressure drop and viscosity occur. The effect of nanoparticles on the flow behaviour of crude oil is also investigated and simulated numerically by computational fluid dynamics using the ANSYS Fluent solver. The simulation is carried out for the optimum nanoparticle concentration at different zones along the pipe. The predictions include pressure and velocity distribution. The results are compared with the experimental data to check the accuracy of the model. The model predictions showed a good agreement with experimental data of pressure drop.

***Keywords**: Pressure drop; CFD modelling; Drag reduction; Nanosilica; Crude oil.*

1. Introduction

Crude oil is one of the most important sources of energy that has faced an increase in demand in the world since the last decade; its production has increased to 84 million barrels per day in the past 20 years [1]. It considered as the main provenience of the economy in many countries, especially Iraq which has traditionally provided about 95% of foreign exchange earnings. The most effective, congenital and economical mean for exporting crude oil or transferring to storages or refineries is using pipelines. Although, the high viscosity and density and the presence of high molecular components, brine, and many heavy metals can cause a high-pressure drop. This pressure drop should be lowered to minimize the pump power and keep this type of transportation economical.

Generally, there are three main methods to lower the pressure drop [2]: drag or friction reduction, reducing viscosity and producing an improved Syncrude viscosity by the partial upgrading of the heavy crude oil.

Over many years drag reduction method has been used to reduce the pressure drop for long pipeline system by introducing drag reducing additives like polymers [3], surfactant [4], and fibres [5]. These additives reduce pressure drop by suppressing turbulent eddies formation and reduce the pipeline wall friction [6]. The main challenges of using these additives are selecting the right dosage of addition, their solubility and stability in crude oil as well as its resistance against degradation at high temperature. This challenge limits the use of this method, especially that most of these additives separate from crude oil during storage.

Viscosity reduction method is widely used in most petroleum industry. The mechanism of its work depends on reducing the high viscosity of crude oil to a lighter one to make the transportation easier at lower cost, and this is usually done with different methods like dilution.

The dilution method involves mixing the crude oil with light hydrocarbons like naphtha, kerosene, light crude oils [7]. Solvents like; alcohol and methyl are also investigated as viscosity reducer [8-9], but this method requires rigorous maintenance since most of these diluents tend to corrode pipelines and storage systems [10]. Core annular flow is also used to reduce the friction between the fluid and the wall of the pipe, the technique depends on putting the crude oil in the centre of the pipe and separates it from the wall by film layer of water or another solvent which acts as a lubricate. This method reduces the presser drop to about 90% from that without using lubricate [11-12]. The limitation of this method involves the formation of waves as well as the difficulty to get perfect annular flow due to the radial movement of the core especially when the difference of density between the crude oil and lubricate is very large [13]. Heating method is also used to reduce the high viscosity of crude oil depending on the effect of high temperature on viscosity and to lower the resistance of the oil to flow in a pipe [14]. However, this method consumes high energy for heating, and it is not suitable for transferring oil in the subsea pipeline due to the cooling effect of the surrounding water.

Another technique that has been used to improve the flowability of heavy crude oil is the formation of oil in water emulsion with the addition of a specific surfactant [15-16]. This method has been used in the ORIMULSION_ process developed by PDVSA (Petroleos de Venezeula) in the 1980s [6]. The main difficulties in applying this method are the cost and the selection of suitable surfactants to keep on the stability of emulsion during transferring process and the difficulty of separating water and surfactant from crude oil.

The magnetic and electric field is also investigated to reduce the high crude oil viscosity [17-21]. These techniques reduce the viscosity for several hours. The magnetic field has an effect on some heavy hydrocarbons like paraffin, while electric field has an effect on both of asphaltene and paraffin. The reduction of viscosity depends on aggregation of such compounds in crude oil into large ones causing a change in the rheological properties of crude oil that leads to decrease viscosity. This method is suitable for pipeline transporting, especially in deep water [17].

Nanotechnology is applied in many oil and gas industry, upstream (exploration and production) and downstream [21-23]. The nanomaterials are metal with nano size (1-100) nm with unique characterization like; large surface area, high dispersibility, and tunable physicochemical characteristics. The effect of these materials on the viscosity of crude oil has been investigated laboratory and at field condition of the reservoir. One of the most effective nanomaterials is oxide silicate nanomaterial SiO_2. Other researchers showed that this material has a high adsorptive capacity to asphaltene molecules after testing it in core flooding at reservoir conditions [24-25].

Computational fluid dynamics (CFD) have gained a great attention in the last decade as a simulation tool to predict the flow behaviour in pipes. Most of the researcher used CFD techniques to simulate liquid-liquid flow [26-30]. CFD is also used to predict liquid-solid flow. The Eulerian multifluid model approach was developed for liquid-solid flows [31-32]

Recently, a computational fluid dynamics (CFD) simulation technique is used in the nanofluid field. Since solid and liquid exist in nanofluid flow, it can be considered as a two-phase flow with the considering of nanoparticles as a secondary phase [33]. Anwarbeg [34] used CFD to simulate the laminar convection of Al_2O_3–water bio-nanofluids in a circular tube using a single phase model and three models of two phase (volume of fluid, mixture and Eulerian). The laminar flow of nano fluid in a micro-channel was also simulated using the Eulerian two-phase model [35].

In spite of the above studies on using nanotechnology in reducing the viscosity, studying their effect in the dynamic condition is still under search and seeks more study. Hence, the aim of this research is to investigate the effect of locally prepared SiO_2 on the mobility of Iraqi crude oil under the dynamic condition as a drag reducer. Indeed, this effect is also investigated numerically using CFD.

2. Materials and method

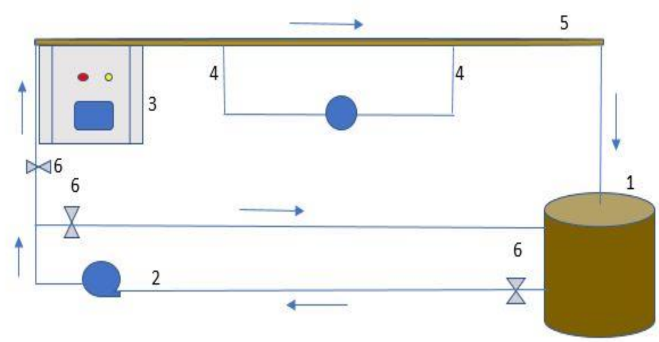
2.1. Materials

Two materials were used in this research; Iraqi crude oil named Basrah heavy supplied from Al-Dora refinery with specifications listed in Table 1 and nano silica (NS) with particle size of 30 nm, and specific surface area of 40 m^2/gm was used. The nanoparticles were prepared locally, and its specifications are available in previous work [36].

Table 1. Physical properties of crude oil supplied from Al-Dora refinery

Sp.gr at 15.6°C	0.8697	Asphaltenes content (wt %)	2.83
API at 15.6 °C	31.2	Vanadium (ppm)	59.4
Density at 15°C	0.8692	Nickel (ppm)	18.14
Kin. viscosity at 10 °C (cSt)	30.5		

2.2. Experimental procedure



1- Tank, 2- Pump, 3- Control unit, 4- Pressure transducer, 5- Pipe, 6- Valve.

Figure 1. Experimental system layout

The schematic diagram of the experimental rig is shown in Fig.1. It consists mainly of stainless steel pipe of 4 m length, and 4.5 cm inside diameter, positive displacement oil pump, solenoid valve, and pressure transducers. The viscosity was measured using viscometer also sensitive electronic balance was used. The effect of nano silica (NS) addition on the flow behaviour of crude oil was studied at concentrations (0, 50, 100, 150, 200, 300, 400, 500, 600, and 700) mg/L. The experiments were carried at constant flow of mixture 0.2m/s. These samples were prepared using a magnetic stirrer and an ultrasonic device. The specifications of these devices are listed in Table 2.

Table 2. Specifications of experimental devices- circulating flow system specifications

Solenoid valve	Size	1/4
	Type	S 101001018N
	Orifice	1.8 mm
	Pressure	0-16 bar
Oil pump	Model	WCB 30
	Capacity	30 L/min
	Power	370 W
	Voltage	220 V 50 Hz
	Head	30 M
Pressure transducers	Model	CPC6000/Barometer
	Range	0-10 bar
	Output	4-10 mA
Viscometer	Type	Fensk- Canon
	Size	200
	Constant	0.1 cSt/s
	Range	From 20 to 100 cSt
Ultrasonic machine	Type	KQ3200E
	Power	220 V, 50 Hz
	Frequency	40 KHz
	Sonication power	150 W
	Volume	6 L

3. CFD modelling

A three-dimensional model was developed using ANSYS (R17 and R18.2) FLUENT solver with double precision to study the flow behaviour of crude oil in the pipe with different concentrations of nanosilica (NS). The geometry was built using the real dimensions of the pipe, as shown in Figure 2. Meshing was attained in medium smoothing; excellent skewness (min. of 0.005157, and max. of 0.456); no. of nodes was 179350, and no. of elements were 169800, the pipe mesh was shown in Figure 3. The Eulerian-Eulerian approach was constructed to characterize the liquid and solid particles of the multiphase flow. FLUENT settings are pressure solver with absolute velocity formulation. A model is standard K-ε (2 eq.) with simple solution scheme. Second order upwind momentums, first order turbulent kinetic and standard pressure discretizations were implemented. Nanoparticles are assumed to be in equilibrium with the liquid phase, and the relative velocity between phases can be neglected. This because nano silica particles are very small (particles diameter ≤ 30 nm) thus; the nanofluid behaves like a homogeneous mixture, and a single phase Navier- Stokes equation can be used. The liquid properties for water with (50-700 mg/L) of nano silica concentrations and the viscosities of crude oil at each concentration were measured experimentally and included in the model.

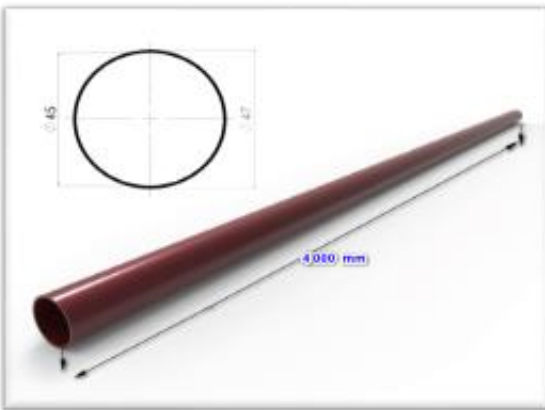


Figure 2. Geometry of the pipe

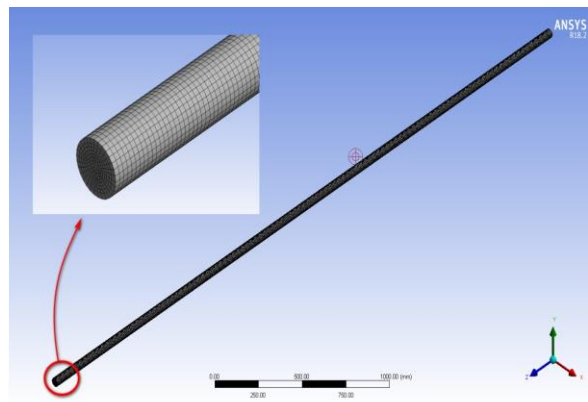


Figure 3. Pipe meshing

4. Results and discussion

4.1. Effect of silica nanoparticles concentration on crude oil viscosity and pressure drop

The effect of nano silica (NS) addition as a flow improver on the viscosity of Iraqi crude oil is shown in Figure 4. A sharp decrease of viscosity values (up to 24.5 cSt) can be noticed with the addition of nano silica up to the optimal concentration of 100mg/L. This decrease can be due to the ability of nanoparticles to adsorb on the surface of asphaltene, which inhibits the self-aggregation of such compounds as well as changes in the molecular structure, which causes a decrease in the viscosity value. This result is in line with other works [37-38].

Increasing NS concentration above optimum concentration value (up to 200mg/L) causes a sharp increase of viscosity value (30cSt), while a further increase of nano silica concentration leads to a gradual increase of crude oil viscosity. This increase can be explained by the tendency of nanoparticles to aggregate due to the increase of the packing factor of these particles. This can reduce the interaction energy among asphaltenes aggregation.

The change of the viscosity values associated normally with altering in Reynolds number values as shown in Figure 5, which shows that maximum value is with 100ppm addition. However, the flow stayed in transition region

The change of the viscosity values associated normally with altering in Reynolds number values as shown in Figure 5, which shows that maximum value is with 100ppm addition. However, the flow stayed in transition region. The pressure drop inside the pipe is a very important phenomenon in fluid flow; it relates to pumping power consumption of crude oil. Pressure drop is highly dependent on the viscosity of the fluid; as the viscosity decreased, the fluid layers are slide over each other with less friction with pipe walls and saving in pumping energy. Figure 6 shows the pressure drop values as a function of nanosilica concentration. The lowest value of pressure drop is (3.12 Pa) at the optimum concentration of 100 mg/L.

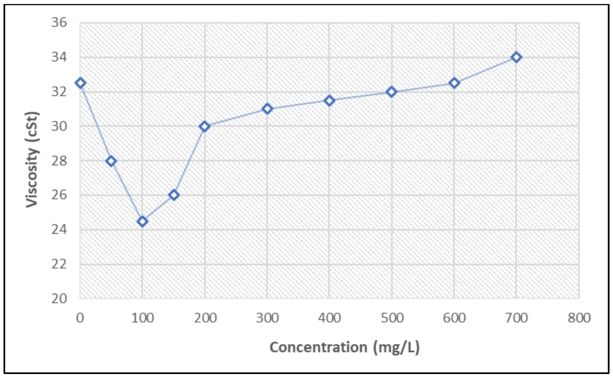


Figure 4. Effect of NS concentration on crude oil viscosity

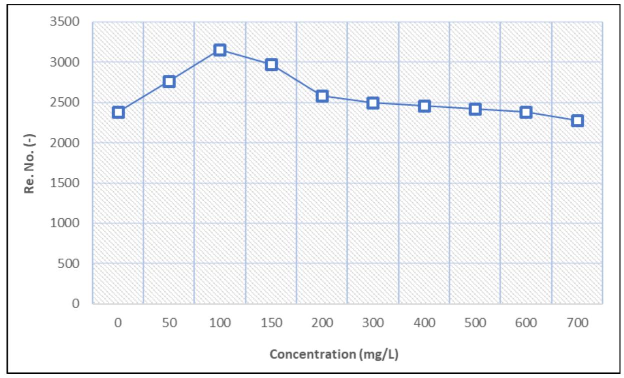


Figure 5. Reynolds number values as a function of NS concentration

4.2. CFD simulation results

4.2.1. Pressure and pressure drop

The pressure drop along the pipe was calculated theoretically by CFD for all NS concentrations, and the results are shown in Figure 6. The experimental and theoretical values are close to each other, with a standard deviation of 0.63.

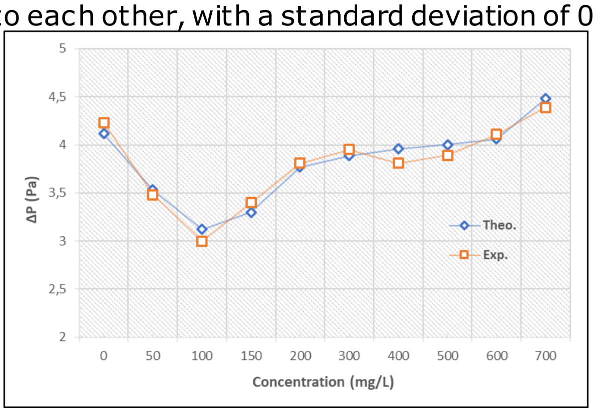


Figure 6. Effect of NS concentration on differential pressure

The results of pressure distribution along the pipe are shown in Figures (7-8) for crude oil without nano silica (NS) addition and with optimum addition concentration, respectively. Pressure contours show clearly the effect of NS addition at the desired concentration on fluid flow pressure and hence, on pumping power consumption. The pipe is divided into five positions in order to show the pressure distribution along the pipe as (inlet, Z=1m, Z=2m, Z=3m, and outlet). It is obviously shown that the pressure at a position of Z=1m is greatest in the case of flow improvement by nanoparticles addition at optimal dosing than that without flow improvement.

Using pressure outlet boundary and 1 atm inlet pressure gives the differential pressure distribution from inlet zone to outlet of the pipe; more efficient flow conditions are at optimum NS concentration resulting in much more effective pressure as shown in Figure 8. Pressure contours at positions: Z=1m, Z=2m, and Z=3m at different concentrations of improver are shown in Figures (9-11). The pressure distribution along the pipe shows the efficiency of NS as a flow improver for crude oil because the differential pressure is an indication of flow energy inside a pipeline. As mentioned above, the reduction in viscosity of crude oil as a result of NS addition introduces a significant reduction in friction, and hence lower pressure drop is obtained. The results obtained are matching the results of [1].

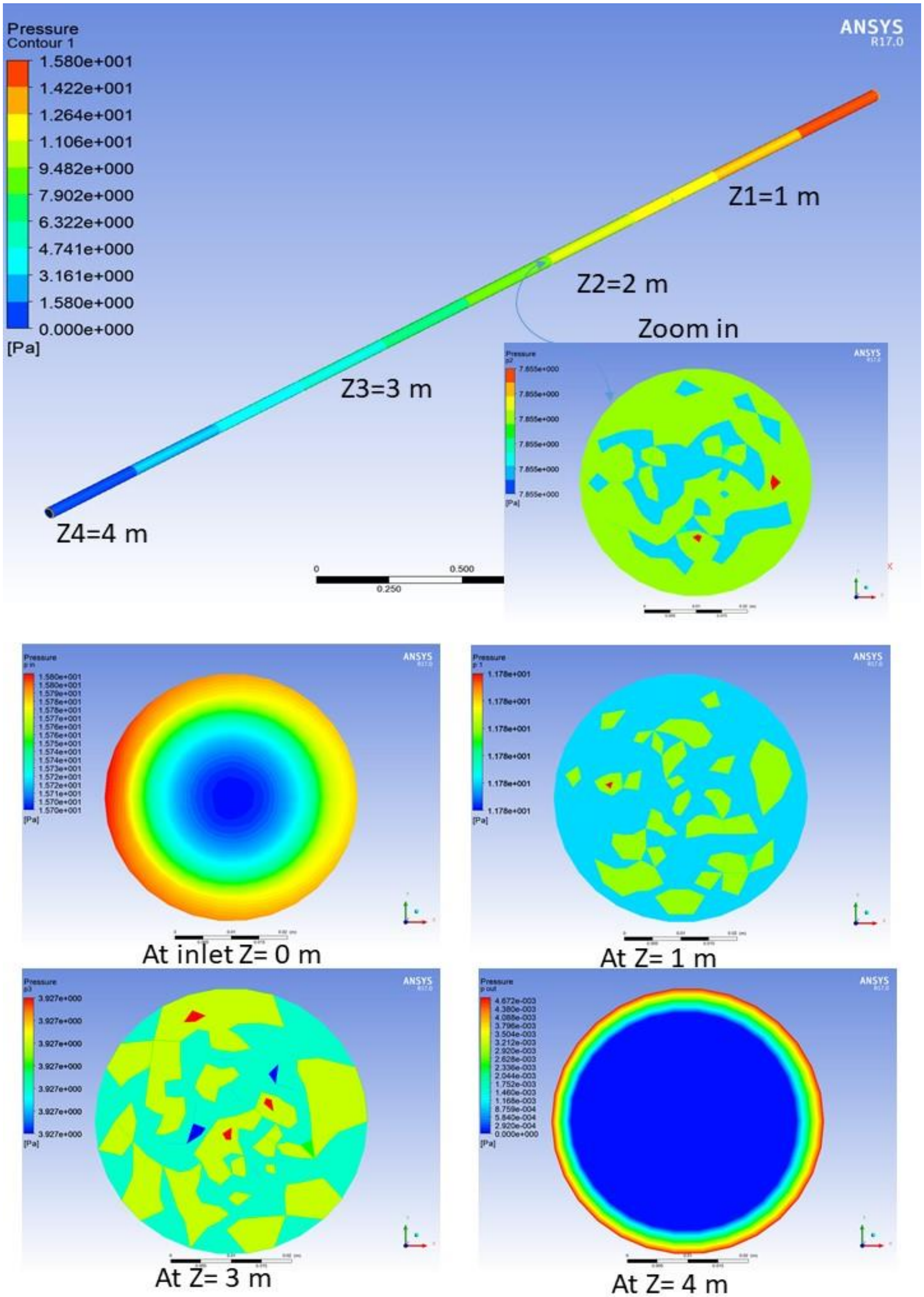


Figure 7. Pressure contours for the crude oil without NS

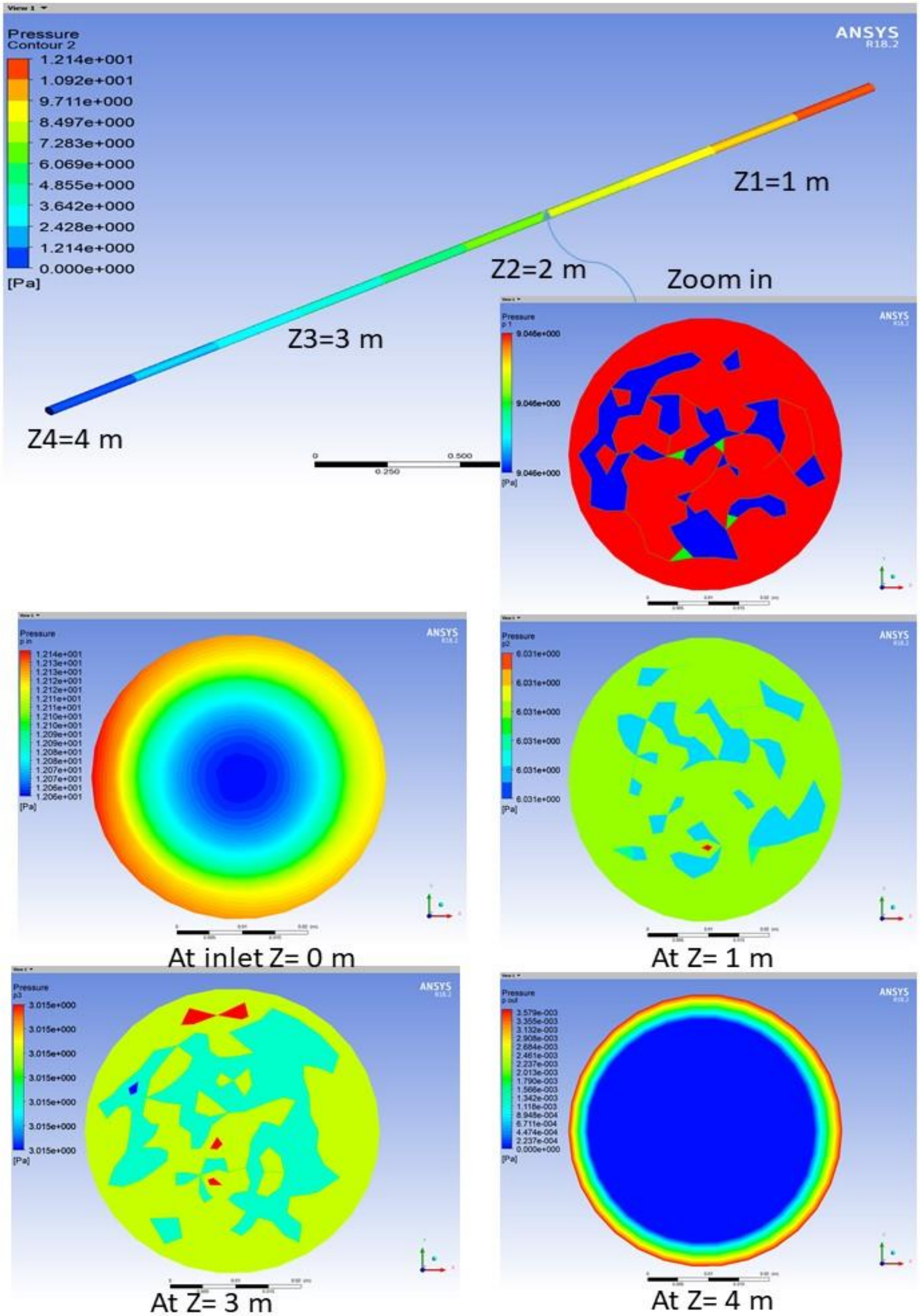


Figure 8. Pressure contours for the crude oil with optimum NS concentration

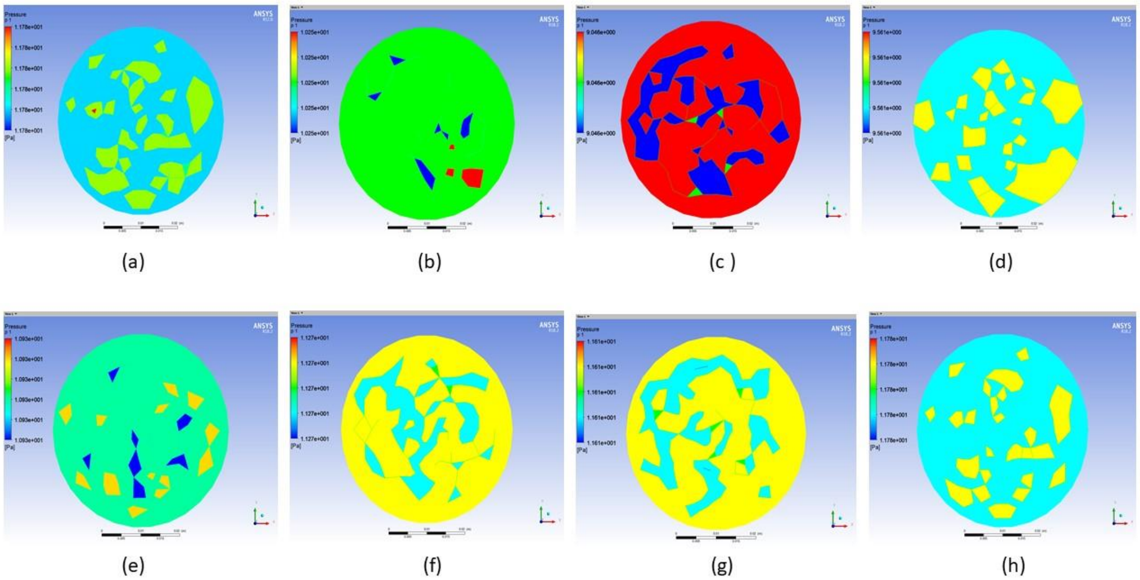


Figure 9. Pressure contours at a position of Z=1m for a) crude oil, b) crude oil+50 mg/L of NS, c) crude oil+100 mg/L of NS, d) crude oil+150 mg/L of NS, e) crude oil+200 mg/L of NS, f) crude oil+300 mg/L of NS, g) crude oil+500 mg/L of NS, h) crude oil+700 mg/L of NS

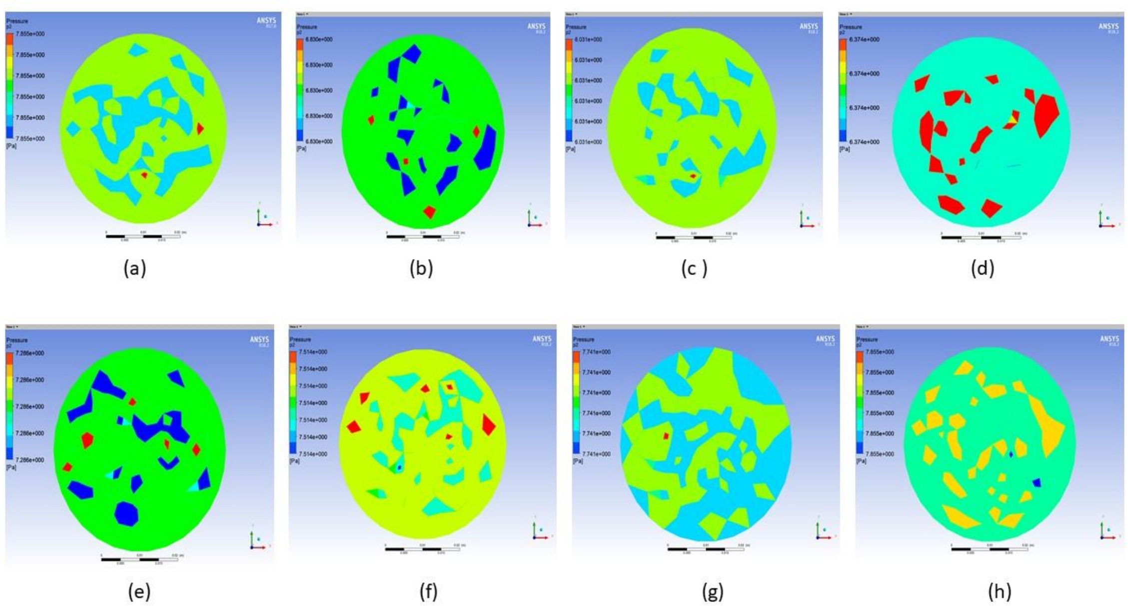


Figure 10. Pressure contours at a position of Z=2m for a) crude oil, b) crude oil+50 mg/L of NS, c) crude oil+100 mg/L of NS, d) crude oil+150 mg/L of NS, e) crude oil+200 mg/L of NS, f) crude oil+300 mg/L of NS, g) crude oil+500 mg/L of NS, h) crude oil+700 mg/L of NS

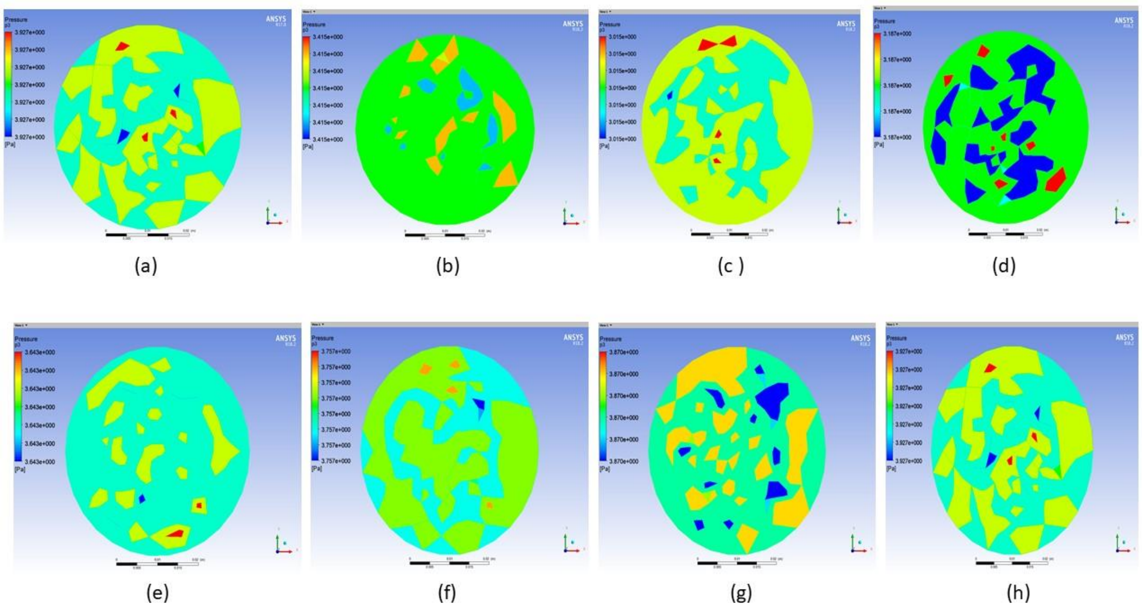


Figure 11. Pressure contours at a position of Z=3m for a) crude oil, b) crude oil+50 mg/L of NS, c) crude oil+100 mg/L of NS, d) crude oil+150 mg/L of NS, e) crude oil+200 mg/L of NS, f) crude oil+300 mg/L of NS, g) crude oil+500 mg/L of NS, h) crude oil+700 mg/L of NS

4.2.2. Velocity distribution

The velocity of crude oil does not change because that NS addition affects the pressure drop or differential pressure inside the pipe, and the velocity is constant at inlet velocity of 0.2 m/s. The velocity remains approximately constant throughout the work. Velocity contour and vector are shown in Figures (12-13), as the no-slip condition on the wall was applied the velocity is maximum in the centre of the pipe decreases towards the pipe wall. The results are in accordance with experimentation since the velocity, and hence the flow rate remains constant during the experimental work. The results are also matching the results obtained by [33].

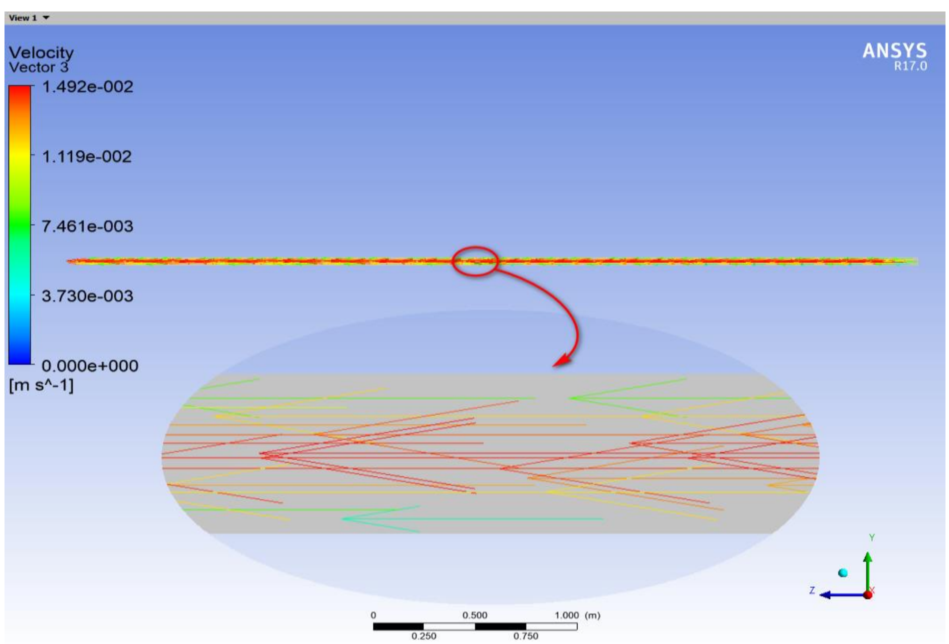


Figure 13. Velocity contour of the crude oil sample inside the pipe at different positions

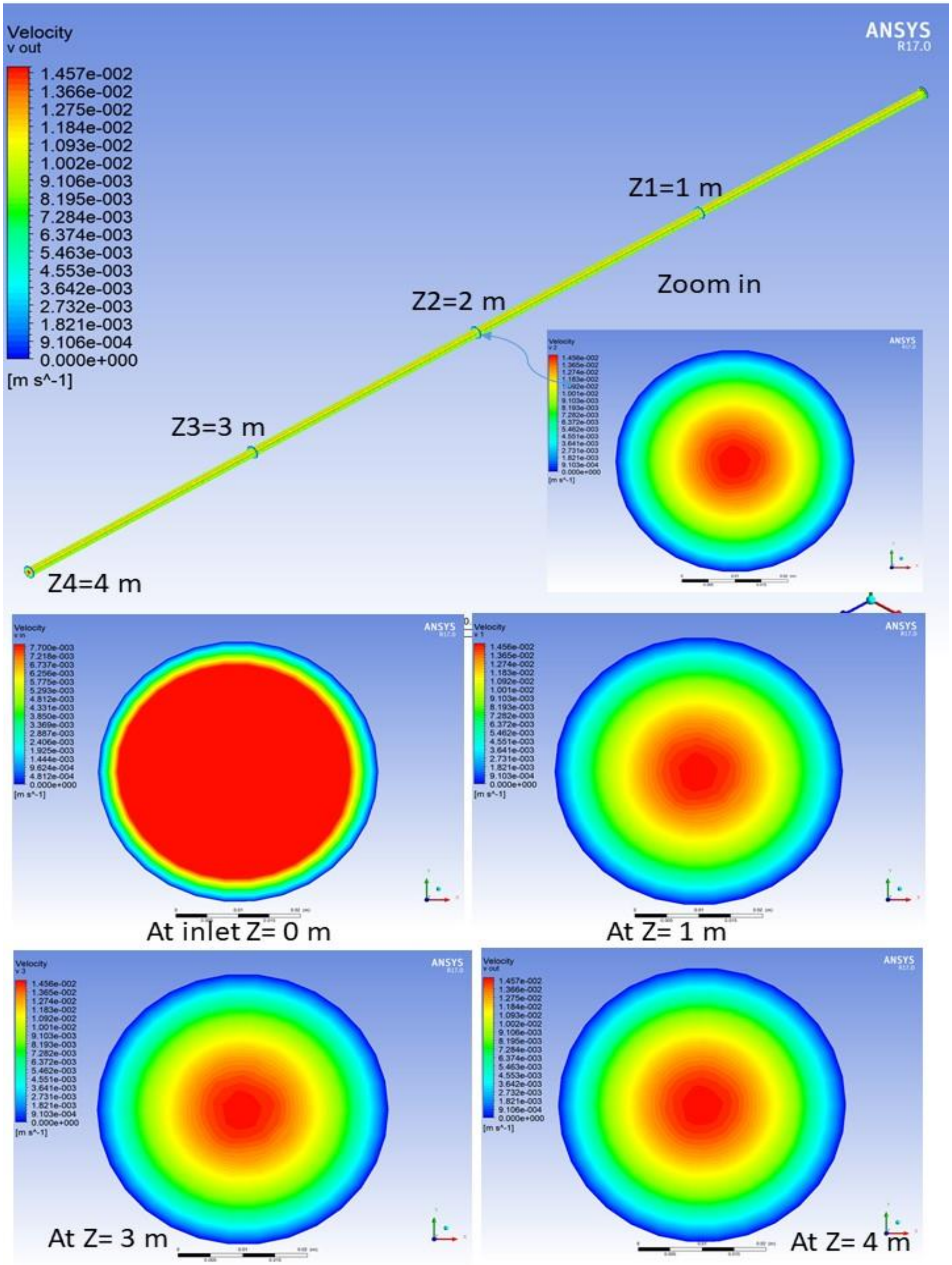


Figure 12. Velocity vector of the crude oil sample inside the pipe at Z=2m

4.2.3. Solution convergence:

The results are converged after nearly 200 trails for residuals, continuity equation, velocity, k, and ε for all cases, as shown in Figure 14. This convergence in the results indicates the suitability of the model for solving the problem rather than the compatibility of boundary conditions and meshing scheme. The convergence criteria prove a satisfactory accuracy and stability have been revealed. The results agree with [33].

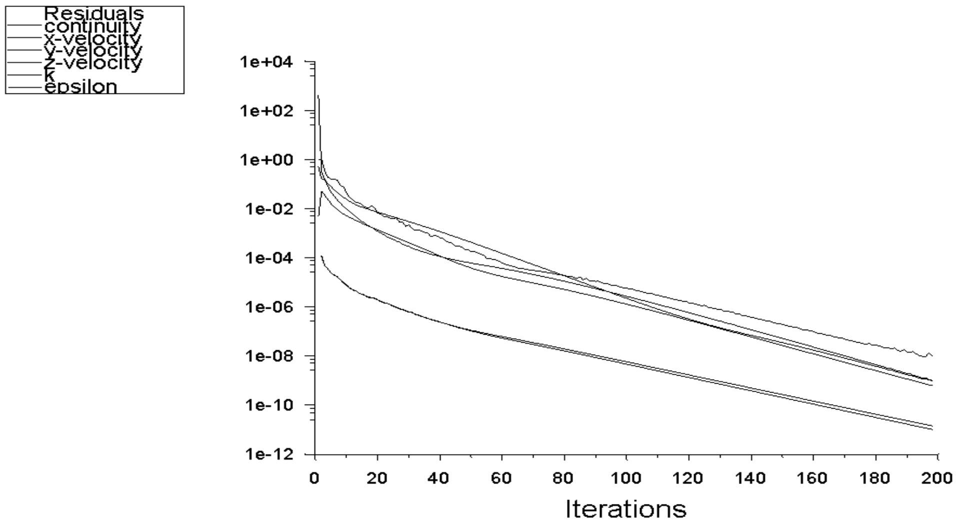


Figure 14. Solution convergence

5. Conclusions

Silica nanoparticles proved to be efficient and suitable to enhance the fluidity of Iraqi heavy crude oil at a constant temperature of 20°C. The results showed that the presence of NS in optimal dose (100 mg/L) resulting in a lower pressure drop of (3.122 Pa) and viscosity of (24.5 cSt) that reduced by 24% than that without NS. Flow improvement criteria are a result of viscosity reduction and friction suppression. CFD confirmed its effectiveness as a simple and efficient tool to describe the flow behaviour inside the oil pipe when the second phase of nano-sized solid particles are present. CFD simulation analyzed the velocity distribution as well as pressure drop at different zones of the pipe with good agreement with experimental data.

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