Numerical study and sensitivity analysis of two-phase oil-water flow and heat transfer in different flowline orientations using OpenFOAM

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ARTICLE INFO

Keywords:
Flow pattern
Heat transfer
Flowlines
Two-phase flow
Global sensitivity analysis

ABSTRACT

Evaluating the oil-water temperatures in flowlines is demanding mostly in deep offshore applications where flow assurance issues and dramatic heat transfer are anticipated to occur. Consequently, a 3-D mathematical model of oil-water Newtonian flow under non-isothermal conditions is established to investigate the mechanisms of the two-phase oil-water transportation and heat transfer in horizontal and inclined flowlines. In this study, a non-isothermal two-phase flow model is first modified and then implemented in the InterFoam solver by introducing the energy equation using OpenFOAM® code. The Low Reynolds Number (LRN) k-ε turbulence model is employed to resolve the turbulence phenomena within the oil and water mixtures. The flow patterns, local heat transfer coefficients (HTC), and relative errors for two-phase oil-water flow at different flowline orientations (0°, +4°, +7°) are compared with the experimental literature results. The model was also employed to ascertain the effect of input water cuts and flowline inclinations on the flow regimes, and the results were validated in literature with a high accuracy level. Global sensitivity analysis is then conducted to determine the effect of the different parameters on the output temperature and pressure of the produced two-phase hydrocarbon systems. Subsequently, HTC and flow patterns for oil-water flows at different inclinations of -10°, -4°, and +10° can be predicted by the model. The velocity distribution, liquid holdup, pressure gradient, and temperature variation at the flowline cross-sections are simulated and analyzed extensively.

Nomenclature

\( k \) turbulence kinetic energy [m²/s²]
\( Fs \) body force in the axial direction [kg. m/s²]
\( g \) gravity [m/s²]
\( p \) pressure [kg/m²/s²]
\( U \) velocity [m/s]
\( T \) temperature [K]
\( c_p \) specific heat capacity [J/(kg. K)]
\( q'' \) heat flux [w/(m². K)]

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https://doi.org/10.1016/j.csite.2022.102465
Received 7 July 2022; Received in revised form 19 September 2022; Accepted 3 October 2022
Available online 18 October 2022
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1. Introduction

Exploiting hydrocarbon resources in an adverse and subsea deepwater environment has been driven by the continuous increase in
energy demand and depletion of already existing conventional oil-gas reserves [1–3]. Two-phase flow in pipelines is normally experienced in the nuclear, chemical, and petroleum industries, mostly in the power generation, combustion systems, and crude oil transportation through different pipeline orientations [4,5]. Transportation of this two-phase hydrocarbon through such environments (about 4–5 °C) which creates many flow assurance issues usually requires long flowlines [1,6,7] as shown in Fig. 1.

Flow assurance in the petroleum industry is one of the biggest problems bedeviling hydrocarbon production and this can cause serious challenges to subsea deepwater field developments [8–10]. This type of environment is characterized by low seabed temperature and high hydrostatic pressures, which may influence the flow of the produced hydrocarbon fluids (oil, gas, and water) through the flowline up to the processing facilities [8,9]. In addition, the flowline has sections with different orientations, usually between −10° and +10° due to uneven seabed which affects the flow regimes [11,12] (Fig. 1). Therefore, understanding the behavior of hydrocarbon fluids is significant in oil production and field development.

The subsea heat management system is very important to the successful operations of flow assurance in deepwater petroleum fields [8,9,13,14]. It is required during design to maintain the temperature of the fluid inside the flowlines well above the surrounding temperature. The accurate prediction of temperature and pressure is all-important for the prevention and remediation of flow assurance issues [8,15–17]. One of the most important steps in the design of a subsea facility layout is the heat analysis of a subsea production system, which predicts the flowlines’ temperature profile [8,10,18]. Heat analysis includes both steady-state and transient studies during different stages of the field’s life and must serve as a standard design tool for heating systems or thermal insulation selection to elude the formation of hydrate and wax [3,8,10,19].

Various technical and scientific research efforts have been established in the studies of heat transfer in pipelines. In the last five decades, most of the published two-phase heat transfer studies focused on gas-liquid in horizontal and vertical pipes [11,15,20,21]. Some are numerical investigations [22–27], while many others carried out experimental studies on the effect of flow rates, flow patterns, and pipe orientations on the gas-liquid heat transfer process [26–30]. The two-phase oil-water flow structure is completely distinct from that of gas-oil flow and this distinction is attributed to the small buoyancy effect and large momentum transfer capacity in the oil-water flows [19,31–33]. Therefore, it is very important to develop new models for the correct prediction of heat transfer and the different factors affecting oil-water two-phase flow phenomena during flowlines design, safety, and optimized operations.

Some theoretical models, empirical correlations, and experimental studies are reported for evaluating the heat transfer of two-phase oil-water flow in pipelines [15,34–37], which is limited when compared to gas-liquid heat transfer. Legan and Knudsen [34] studied the turbulent heat and momentum transfer characteristics of unstable dispersion of oil droplets in water. But the authors’ results were considered only applicable to water-oil dispersions within specified drop sizes, concentrations, and temperature ranges. Also, Legan and Knudsen were only able to predict the heat transfer coefficients and viscosity of a well-mixed oil in water dispersion by equation. The authors couldn’t explain why the relative fluidity of both light oil and heavy dispersions decreases with temperature. Shang and Sarica [15,38–40] developed a mathematical model that predicts the temperature profiles for two-phase oil-water stratified flows. The analytical model was verified by a single-phase heat transfer model and validated against experimental data. The authors reported that the simulated result from the analytical model was only validated for the water cut of 50% and verified for the water cuts of 0 and 100%. Generally, all authors deduced the complication in predicting the heat transfer rate on the complexity of two-phase oil-water flow [41,42].

Several authors have reported the effect of pipe inclination angles on flow patterns [2,43–45], pressure drop [44,46,47], liquid holdup [43,44,46–49], drop velocity [48], drag-reducing polymers [50], and HTCs [41,51,52] in two-phase oil-water flows. Boostani et al. carried out an experimental investigation and artificial neural network (ANN) model to resolve the HTC, and flow pattern for oil-water flows in inclined and horizontal pipelines. Because of the inherent complexity of multiphase flows, it has become difficult to develop a model that can accurately predict the HTC in oil-water flows [41]. To this end, no reported numerical model yet in the open literature has been employed to compute the effect of different flowline inclinations and flow patterns on HTC for two-phase oil-water flow.

With the above-mentioned review, the leading contributions of our model relative to literature works are: (i) Estimating the heat transfer coefficient and flow patterns for oil-water flows at inclinations ranging from −10° to +10° due to limited works focusing on these flowline inclinations. (ii) Ascertain the effect of input water cut and flowline inclinations on the flow regimes using the established model. (iii) Carry out a global sensitivity analysis to determine the impact of the different parameters on the produced two-phase hydrocarbon output pressure and temperature. (iv) Provide information about the two-phase oil-water flow field using a mathematical model of oil-water flow. The model is able of calculating velocity distribution, pressure gradient, liquid holdup, and temperature variation at the flowline cross-sections.

This paper seeks to study the mechanisms of the two-phase oil-water transportation and heat transfer in different flowline orientations. For that reason, a non-isothermal two-phase heat transfer flow model that is vigorous enough to span the fluid combinations, flow patterns, flowline orientations, and flow rates is established to explore the effect of these issues. The LRN k-ε model is employed to simulate the turbulence flow and to account for the near-wall treatment. This model considers the energy and LRN k-ε turbulence equations which are regarded as a more appropriate approach to the heat transfer phenomena and the Low Reynolds input. The model is compared with the experimental data in the literature [41]. The model was also employed to ascertain the effect of input water cuts and flowline inclinations on the flow regimes, and the results were validated in the literature [11]. Afterward, a global sensitivity analysis is performed to determine the effect of the different parameters on the performance of the produced hydrocarbon fluid. The HTC and flow patterns for oil-water flows at different inclinations, velocity distribution, pressure gradient, and temperature variation at the flowline cross-sections are simulated and analyzed extensively. This numerical tool could be globally applied to calculate the properties of the fluid and other operating parameters that are important in the management of two-phase transportation.
2. Mathematical model

Various studies on the hydrodynamics and thermal modeling of different flow behavior and flowline orientations are carried out, focusing on computing the HTC, velocity profile, temperature distribution, pressure drop, liquid holdup, and flow patterns.

2.1. Governing equations

A non-isothermal two-phase Newtonian flow model has been entrenched in this section. The governing equations comprise mass conservation, momentum conservation, and energy conservation equation.

From the foregoing analysis, the mathematical models of non-isothermal two-phase Newtonian flow are expressed below:

2.1.1. Mass conservation equation

The total mass of the oil-water phase is constant at the flowline cross-section in the axial direction. The conservation equation is expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho U) = 0$$

where $\rho$ and $U$ are the density of the velocity of the two-phase fluid.

2.1.2. Momentum conservation equation

Supposing an incompressible two-phase fluid flow, the Navier-Stokes equation in the axial direction of a fully developed flow is expressed as

$$\frac{\partial \rho U}{\partial t} + \nabla . (\rho U U) = \nabla P + \nabla . [\mu \nabla U + \nabla U^T] + \rho g \sin \theta + F_s$$  \hspace{1cm} (2)

$$\frac{\partial \rho a}{\partial t} + \nabla . (\rho a U) + \nabla . (1 - a) a U_s = 0$$  \hspace{1cm} (3)

where $U$ is the velocity in the axial direction, $\nabla P$ is the pressure gradients in the stream’s direction, $g$ is the acceleration due to gravity, $\theta$ is the inclination angle, $\mu_{\text{eff}}$ is the effective dynamic viscosity which is the summation of the molecular and turbulent viscosity ($\mu + \mu_t$), $U_s$ is the relative velocity between phases, $a$ is the fluid volume fraction, and $F_s$ is the body force in the axial direction.

The density and viscosity of the two-phase oil-water flow are explained in each cell by the volume fraction of the oil phase ($a$) below:

$$\rho = a_o \rho_o + (1 - a_o) \rho_w$$  \hspace{1cm} (4)

$$\mu = a_o \mu_o + (1 - a_o) \mu_w$$  \hspace{1cm} (5)

where subscripts $o$ and $w$ represent the oil and water phases, $\rho$ and $\mu$ are the density and dynamic viscosity. The indicator function $a$ is illustrated as:

$$a \begin{cases} 1 & \text{liquid} \\ 0 & \text{transition zone} \\ 0 & \text{gas} \end{cases}$$  \hspace{1cm} (6)

2.1.3. Turbulence model

Due to the characteristics of turbulence in two-phase fluid flow, the turbulent fluctuation imposes additional momentum and energy transfer. Hence, turbulent models are deployed to simulate momentum and energy transfer phenomena. The commonly used turbulence model is the standard $k-\varepsilon$ model by Launder and Spalding [53]. Nonetheless, the model does not give accurate results close to the wall and thus is more suited for high Reynolds number flows. The Low Reynolds Number $k-\varepsilon$ model, by Launder and Sharma [54] is introduced to account for the near-wall treatment by the addition of damping functions into the turbulent viscosity. The turbulent kinetic energy and dissipation are described by:

$$\frac{\partial (pk)}{\partial t} + \text{div} (pkU) = \frac{\partial}{\partial x_i} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k + G_\mu - \rho e - Y_m + S_k$$  \hspace{1cm} (7)

$$\frac{\partial (pe)}{\partial t} + \text{div} (peU) = \frac{\partial}{\partial x_i} \left( \Gamma_\varepsilon \frac{\partial \varepsilon}{\partial x_j} \right) + C_f \rho \frac{\varepsilon}{k} (G_k + G_\varepsilon) - C_2 f_2 \rho \varepsilon^2 k + E + D + S_\varepsilon$$  \hspace{1cm} (8)

where $k$ is the turbulent kinetic energy, $\varepsilon$ is the turbulent dissipation rate, $C_1 = 1.92$, and $C_2 = 1.3$ are the model constants for the low Reynolds number $k-\varepsilon$ model, $f_1$, and $f_2$ are the functions specially employed for the near-wall treatment, $G_k$ and $G_\varepsilon$ are the productions of turbulent kinetic energy, and $Y_m$ is the fluctuation dilatation incompressible turbulence. $\mu_t$ is the turbulent viscosity, $\Gamma_k$ and $\Gamma_\varepsilon$ are effective diffusivities of $k$ and $\varepsilon$. $E$ and $D$ are additional terms to further stabilize dissipation and diffusion in the area of the walls, $S_k$ and $S_\varepsilon$ are the source terms.
\[ \Gamma_k = \left( \mu_\text{in} + \frac{\mu_\text{t}}{\sigma_k} \right) \]  

(9)

where \( \Gamma_k \) is the effective diffusivity of \( k \), and \( \sigma_k \) is the empirical turbulence model constant. \( \sigma_k = 1 \) for the low Reynolds number \( k \sim \varepsilon \) model and \( \mu_\text{t} \) is the turbulent viscosity.

\[ \Gamma_\varepsilon = \left( \mu_\text{in} + \frac{\mu_\text{t}}{\sigma_\varepsilon} \right) \]  

(10)

where \( \Gamma_\varepsilon \) is the effective diffusivity of \( \varepsilon \), \( \sigma_\varepsilon \) is the empirical turbulence model constant. For the low Reynolds number \( k \sim \varepsilon \) model \( \sigma_\varepsilon = 1.3 \).

\[ \mu_\text{t} = \frac{f_\text{t}}{C_\mu} \rho \kappa^3 \frac{\varepsilon}{\varepsilon} \]  

(11)

where \( \rho \) is the density of the fluid, \( C_\mu = 0.09 \) is the model constant. \( f_\text{t} \) is the function utilized for the near-wall treatment.

### 2.1.4. Energy conservation equation

The heat-transfer process particularly with the turbulent flow is useful for both engineering and due to its existence in many industrial applications. Thus energy equation is added to the governing equations. Assuming a quasi-transient state in which the axial heat conductive heat effect is ignored, no added source term in the energy equation. The energy equation is represented as:

\[ \frac{\partial T}{\partial t} + \nabla \cdot \left( \rho C_p U T \right) = \nabla \cdot \left[ \frac{\mu_\text{eff}}{\sigma_k} \left( \nabla T \right) \right] + \nabla \cdot \left[ \frac{\mu_\text{eff}}{\sigma_\varepsilon} \left( \nabla \varepsilon \right) \right] \]  

(12)

where \( T \) is the temperature of the two-phase fluid, \( C_p \) is the specific heat capacity of the two-phase fluid, and \( Pr \) is the Prandtl number.

\[ Pr = C_p \frac{\mu_\text{eff}}{\lambda} \]  

(13)

where \( Pr \) is the Prandtl number, \( \lambda \) and \( \mu_\text{eff} \) are the thermal conductivity and kinematic viscosity of the two-phase fluid respectively.

### 2.2. Boundary conditions

The flowline is initially considered to be filled with water. At the onset of the simulation (time = 0), an equal volume fraction of oil-water was infused at the inlet domain of the flowline with different superficial inlet velocities, the outlet permits the mixed flowing fluids to come out of the domain with a pressure of zero, the fluids at the wall was assumed as a no-slip condition with zero velocity, and the symmetry-plane boundary condition was used in the longitudinal pipe section (X-Z plane). A uniform wall heat flux value ranges from 15,100–24,800 W/m² and at atmospheric pressure (room temperature of about 25 °C). Table 1 gives the boundary conditions for all simulations.

### 3. Numerical method and parametric sensitivity analysis

OpenFOAM v.4.0 was utilized to simulate different two-phase flow cases. The two-phase flow is calculated by using the new solver based on the VOF approach [55]. Turbulence effects and their impact on the flow were performed for all simulations using different RANS models. The LRN \( k-\varepsilon \) turbulence model supporting the low \( y^+ \) approach was utilized for the grid-sensitive studies for accurate near-wall treatment with an automatic switch from a wall function to Low-Reynolds Number formulation by grid spacing [56].

#### 3.1. Model geometry and mesh

A 3D flowline was created with a diameter and length of 0.011 m and 1.8 m respectively, symmetry boundary condition’s domain was chosen aimed at reducing the computational cost. The mesh consisting of structured hexahedral cells is bounded by three types of boundary faces (inlet, outlet, and wall), as seen in Fig. 2a. Both geometry and the structured mesh were created by the blockMesh utility in OpenFOAM.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Inlet</th>
<th>Outlet</th>
<th>Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U )</td>
<td>( U_{w,0} = U_{w,0,inlet} )</td>
<td>( \frac{\partial U_{\text{w,0}}}{\partial x} = 0 )</td>
<td>( U_{w,0,wall} = 0 )</td>
</tr>
<tr>
<td>( T )</td>
<td>( T_w = T_{\text{inlet}} )</td>
<td>( \frac{\partial T}{\partial x} = 0 )</td>
<td>( h = (T_{\text{wall}} - T_{\text{inlet}}) \cdot \frac{\partial T}{\partial x} )</td>
</tr>
<tr>
<td>( P_{\text{vgh}} )</td>
<td>( \frac{\partial P}{\partial x} = 0 )</td>
<td>( P_{\text{vgh,wall}} = 0 )</td>
<td>( \frac{\partial P}{\partial x} = 0 )</td>
</tr>
<tr>
<td>( K )</td>
<td>( k_{\text{w,0}} = k_{w,0,inlet} )</td>
<td>( \frac{\partial k_{\text{w,0}}}{\partial x} = 0 )</td>
<td>( k_{\text{w,0,wall}} = k_{\text{wall}} )</td>
</tr>
<tr>
<td>( \rho_\text{f} )</td>
<td>( \rho_{\text{f,inlet}} = 0 )</td>
<td>( \rho_{\text{f,wall}} = \rho_{\text{wall}} )</td>
<td>( \rho_{\text{f,wall}} = \rho_{\text{wall}} )</td>
</tr>
<tr>
<td>( E )</td>
<td>( \epsilon_{\text{w,0}} = \epsilon_{\text{inlet}} )</td>
<td>( \frac{\partial \epsilon_{\text{w,0}}}{\partial x} = 0 )</td>
<td>( \epsilon_{\text{wall}} = \epsilon_{\text{wall}} )</td>
</tr>
</tbody>
</table>

Table 1: Boundary conditions.
2.67% for dispersion of oil in water. There is no noticeable difference between mesh 4 and 5 in terms of the relative error. Therefore, 3.01% plugs of water in oil, 2.72% for stratified flow with a mixed interface, 3.58% for dispersion of water in oil.

48.13% – 45.58.75% in oil, 45.58.75% and flow direction until obtained results give an acceptable margin. The relative error ranges from 39.75% to 1.80% for plugs of water in oil, 3.5.1. Flow pattern and HTCs for oil-water two-phase flow at different inclinations

3.5. Models validation

Mesh 4 is selected for additional study as a compromise between computational cost and accuracy.

HTCs values at different flow patterns between the experimental data and the different mesh sizes is shown in Fig. 3.

3.4. Grid independence study

To evaluate mesh fineness on the solution to obtain minimum mesh density with good accuracy. Five meshes were created with the blockMesh tool for the mesh sensitivity analyses. The mesh data are summarized in Table 2, and the outcome of the comparisons of the HTCs values at different flow patterns between the experimental data and the different mesh sizes is shown in Fig. 3.

The relative error between the experimental and numerical HTCs reduces as the cell numbers increase both normal to the pipe wall and flow direction until obtained results give an acceptable margin. The relative error ranges from 39.75% to 1.80% for plugs of water in oil, 45.58.75%–1.76% for stratified flow with a mixed interface, 50.29%–2.42% for dispersion of water in oil & oil in water, and 48.13%–2.13% for dispersion of oil in water. It is observed that mesh 4 yields satisfactory HTCs results with a low relative error of 3.01% plugs of water in oil, 2.72% for stratified flow with a mixed interface, 3.58% for dispersion of water in oil & oil in water, and 2.67% for dispersion of oil in water. There is no noticeable difference between mesh 4 and 5 in terms of the relative error. Therefore, Mesh 4 is selected for additional study as a compromise between computational cost and accuracy.

3.5. Models validation

3.5.1. Flow pattern and HTCs for oil-water two-phase flow at different inclinations

The proposed model is compared to the experimental investigation of Boostani et al. [41]. In this work, the authors studied the heat transfer coefficient of oil-water flow in horizontal and inclined (-4°, +7°) pipes. The superficial Reynolds number of the water-phase, \( Re_o \), was maintained at 6772, while the superficial Reynolds numbers of the oil-phase \( Re_w \) varied at intervals. To validate the studied results, the numerical results of flow patterns and HTCs for oil-water two-phase flow at different flowline inclinations are compared with experimental data. Accordingly, the thermo-hydrodynamic calculations are both tested and established.

Fig. 5a gives the oil-water flow pattern maps for different flowline orientations (-9°, -6°, 0°, +4°, +7°), classified in line with the definitions of Boostani et al. [41] and Oddie et al. [2]. The observed flow patterns are stratified flow (ST), stratified flow with a mixed interface (ST & MI), plugs of oil in water (Po/w), plugs of water in oil (Pw/o), dispersion of oil in oil & oil in water (Dw/o & o/w), and dispersion of oil in water (Dw/o), annular mist (AN) flows. The oil-water physical properties are described in Table 3.

To corroborate the accuracy of the computation code to reproduce the experimental measurements of Boostani et al. [41], the highlighted cases in Fig. 4a are simulated. Table 4 illustrates a results comparison between numerical and measured flow patterns visualized at different \( Re_\text{sw} \) (≈450–3750) and \( Re_\text{so} \) kept at 6772. The non-isothermal two-phase flow model predicted the observed flow patterns of oil-water flow very reliably. For instance, in horizontal flow, the performance of the model was remarkably good for all Po/w, ST & MI, Dw/o & o/w, and Dw/o are predicted correctly by the 3D models.

Fig. 4b explains the comparison between the numerical and measured HTC values under various \( Re_\text{sw} \) of around 450–3750 when the
Re\textsubscript{sw} is 6772 at different flow inclinations (0°, +4°, +7°). The numerical HTC results are slightly different from the experimental values as the flow patterns change from Po/w to Dw/o. The relative errors between the calculated HTC and experimental results at Re\textsubscript{sw} of approximately 450, where there is a decrease of HTC due to flow pattern change from Po/w to ST & MI is roughly 1% for the 3D model.
Table 3
The physical properties of oil and water.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil density</td>
<td>798</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Water density</td>
<td>1000</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Oil kinematic viscosity</td>
<td>$3.1203 \times 10^{-5}$</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>Water kinematic viscosity</td>
<td>$1 \times 10^{-6}$</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>Oil-specific heat</td>
<td>2050</td>
<td>m$^2$/s$^2$ K</td>
</tr>
<tr>
<td>Water-specific heat</td>
<td>4184</td>
<td>m$^2$/s$^2$ K</td>
</tr>
<tr>
<td>Oil Prandtl number</td>
<td>37.811</td>
<td></td>
</tr>
<tr>
<td>Water Prandtl number</td>
<td>6.90</td>
<td></td>
</tr>
<tr>
<td>Oil-water Interfacial tension</td>
<td>$3.7 \times 10^{-2}$</td>
<td>N/m</td>
</tr>
</tbody>
</table>

Fig. 4a. Flow patterns map for oil-water two-phase flow system with highlighted simulation points.
9

At a flowline angle of about 1280, the relative error for the horizontal flowline where the HTC value is higher than the inclined flow is ~ 2% for the 3D model. Also at a Re of around 3300, Dw/o is only observed within this region because of higher turbulence forces and the relative error is around 3%. In summary, the results of the relative errors obtained between Boostani’s data and the numerical model are within 3%, which demonstrates the model’s accuracy as shown in Fig. 4c.

3.5.2. Inclined two-phase oil and water flow at different input water cuts

A flow pattern map for different angles and input water fractions is established to underscore the effect of flowline inclination. Fig. 4d describes the oil-water flow pattern for different angles ranging from −10° to +10°, input water cut from 10 to 90%, and a constant mixture velocity of 1 m/s. The flow pattern map is constructed and classified according to the description of Amundsen [11], the observed flow regimes are stratified flow with a mixed interface (ST & MI), dispersion of water in oil & water (Dw/o & w), dispersion of oil in water & oil (Do/w & o), and plug flow (PG).

The predicted flow patterns at ±5° and +10° are compared with the experimental data of Amundsen [11] as shown in Table 5. Amundsen investigated the oil-water flow pattern for different angles ranging from −10° to +10°, input water cut from 10 to 90%, and a constant mixture velocity of 1 m/s using a pipe length of 0.4 m long and diameter of 0.056 m. The present study’s prediction of stratified flow ST & MI, PG, and Do/w & o flow patterns are identical from 10 to 90% which supports the accuracy of the model. For an input water cut of 10%, the stratified flow (ST & MI) is observed to generally have a low water fraction in the upper section of the flowline. At some inclinations, there is a dispersion of oil and water in the lower part of the flowline and at other inclinations, there is a clear water layer revealing Do/w & o and ST & MI flow patterns respectively. Modifying the flowline angle from 0° and ±1° increases the dispersion of oil in water at the bottom of the pipe and the Do/w & o flow regime appears where the greatest effect is observed at −1. The phase fraction curves at input water cut from 20 to 80% give a steepest phase fraction gradient for upward moving flow at high inclinations. This implies, that the classified ST & MI flow has a larger amount of mixing and/or waves at the interface at ±5° and ±10° inclination angles compared to the horizontal and downward flow. The height of the water continuous phase at 30% input water cut is highest at ±5° and ±10° and lowest at −10° flowline inclinations: This is owing to the gravitational force working in the opposite direction of the flow in the upward flowline inclination resulting in the accumulation of water. A water layer at the bottom of the flowline emerges when the flowline inclination changes from ±1° to ±5° and ±10°. The phase fraction reveals a plug flow (PG) regime at ±10° flowline angle and an input water cut of 80%.

Furthermore, Do/w & o flow regimes are observed at 10% and 80% input water cut and flowline inclination equal to ±5° to ±10°. For the inclination range investigated, a denser dispersion of oil and water exists from the flowline center up to the top of the pipe. There are no big differences noticed between the inclination angles, an increase in water fraction near the top wall is seen for all inclinations.

![Fig. 4b. HTC variation at different flowline inclinations as a function of Reav](image_url)
Fig. 4c. Predicted values with a numerical model versus experimental values plots for all data and studied inclined positions.

Fig. 4d. Map describing flow pattern as a function of inclination angle and input water cut.

Table 5
Flow pattern in inclined flowline at different water cut-present work vs experimental.

<table>
<thead>
<tr>
<th>Water cut [%]</th>
<th>-5° Exp</th>
<th>3D Predict</th>
<th>+5° Exp</th>
<th>3D Predict</th>
<th>+10° Exp</th>
<th>3D Predict</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
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<td>ST&amp;MI</td>
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<tr>
<td>25</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
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<tr>
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<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
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<tr>
<td>40</td>
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<td>ST&amp;MI</td>
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<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
</tr>
<tr>
<td>50</td>
<td>ST&amp;MI</td>
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<td>ST&amp;MI</td>
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<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
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<tr>
<td>85</td>
<td>Dw/o&amp;w</td>
<td>Dw/o&amp;w</td>
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<td>Dw/o&amp;w</td>
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<td>Dw/o&amp;w</td>
<td>Dw/o&amp;w</td>
<td>Dw/o&amp;w</td>
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<td>Dw/o&amp;w</td>
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</table>
3.6. Sensitivity analysis method

3.6.1. Sensitivity analysis theory

A comprehension of the behavior of hydrocarbon fluids is crucial during field development and production. Therefore, the performance of the hydrocarbon transportation system through environments with high hydrostatic pressures and low seabed temperatures depends on parameters such as flowline inclinations, diameter, roughness, velocity, slip ratio, pressures, flow pattern, holdup, temperature, density, viscosity, specific heat capacities, thermal conductivities, heat flux, etc. It has become difficult to study these parameters knowing well that most of them can be arduous to accurately measure or predict. Consequently, sensitivity analysis is essential to determine beforehand the importance of the input parameters acting individually or in combination and must be factored in during field and laboratory studies.

Sensitivity analysis is generally embraced as a necessary aspect of good modeling practice, and amongst the reasons for using sensitivity analysis are: to identify factors that are unimportant to model output and can be removed from further analysis; to identify the factors that have the most impact on model output; to determine if a model reproduces known effects upon the processes it is simulating; to identify factors that may require more research to enhance confidence in model output; to discover the optimal regions within the parameter space for use in calibration studies; to determine which, if any, factors or groups of factors interact with each other; to establish regions in the space of inputs where the variation in model output is maximum; finally to demonstrate if model predictions are robust to plausible variations in input factors. Different sensitivity analysis techniques exist in a wider range of scientific investigations [57]. Saltelli et al. [58] described three major groups:

- Screening: a qualitative sensitivity analysis method
- Local: a quantitative analysis (factorial design) method varies parameters successively around nominal values.
- Global: quantitative analysis (variance-based) methods that vary all parameters examined in their variation ranges.

In this study, the local sensitivity analysis is chosen as the most appropriate technique due to:

- The number of input parameters,
- The computational cost of running the model, and
- The settling for the analysis.

Local sensitivity analysis of the two-phase flow in the flowline using the thermohydraulic model is conducted using the factorial design method. The local sensitivity analysis involves the uniform distribution of input data by random sampling and it also allows for the interaction between two or more input parameters to be investigated. Decision makers who utilize thermohydraulic model results can justly request thorough analysis results to reasonable variations in the model inputs. This information can be employed to target data acquisition and engineering design decisions effectively by identifying key parameters that impose the greatest influence on system performance.

3.6.2. Factorial design

The factorial design method investigates small changes around nominal value(s). The required total number of simulations is $2^n$, where $n$ is the number of input parameters, and each input parameter is altered in a range of 10% by $+\Delta$ and $-\Delta$ around the nominal value(s) [59]. The response of the system would depend on the results of the simulations. In our case, six input parameters have been selected for the sensitivity analysis. These parameters are flowline inclination ($\theta$), the minimum and maximum superficial oil velocity ($U_{\text{sw}}$), the thermal conductivity of oil ($\lambda_o$), the thermal conductivity of water ($\lambda_w$), and the wall heat flux ($q''$). The linear regression model using the factorial design method is expressed as:

$$ y_o = c_0 + \sum_{j=1}^{n} c_j x_j + \sum_{j=1}^{n} \sum_{k=j+1}^{n} c_{jk} x_j x_k + \cdots + c_{123\ldots6} x_1 x_2 \cdots x_6 $$

where $n$ is the number of input parameters, $y_o$ is the estimated response by the model, $C$ is the coefficient of the polynomial, and $x_j$ is the $j$th input parameter.

Therefore, with six input parameters, equation (14) becomes:

$$ y_o = c_0 + \sum_{j=1}^{6} c_j x_j + \sum_{j=1}^{6} \sum_{k=j+1}^{6} c_{jk} x_j x_k + \cdots + c_{123456} x_1 x_2 x_3 x_4 x_5 x_6 $$

Each of the six input parameters of the model reported above is estimated at 10% (+1) higher and 10% (−1) lower around each nominal value(s). As a result, 64 ($2^6$ factorial) simulations must be executed. $y_o$ can be written into the matrix form from Eqn. (15) as shown.

$$ y_o = CX $$

The coefficient of the matrix which determines the relevance of each input parameter becomes

$$ c = X^{-1} y_o $$

The established numerical model was utilized for the predictions by applying the sensitivity analysis technique.
4. Results and discussion

4.1. Sensitivity analysis result

The global sensitivity analysis method explained in the above section is then applied to the validated numerical model. The minimum superficial liquid velocities were utilized to determine the flow pattern boundaries. ST flow pattern is selected for minimum \( U_{so} \) and minimum \( U_{sw} \). The results are presented in decreasing order by using the Pareto chart to describe the importance of each parameter and their interactions. Table 6 shows the selected nominal values and their respective variations from the input parameters of Boostani’s experimental work employed for the sensitivity analysis.

4.1.1. ST flow pattern

This flow pattern represents the region of the minimum possible values for both superficial oil and water velocities in horizontal flowlines as shown in Table 6. Fig. 5a and 5b describe the effect of each parameter and its interactions on the outlet pressure and temperature. The outlet pressure \( (p_{outlet}) \) in Fig. 5a is noticed to be mainly affected by the superficial oil velocity \( (U_{so}) \), followed by the parameter combination of \( U_{so} \), \( U_{sw} \), then superficial water velocity \( (U_{sw}) \). The flowline inclination \( (\theta) \) has the most inverse influence on the outlet fluid pressure followed by the combinations of \( \theta U_{so} U_{sw} \), \( \theta U_{sw} \), and \( \theta U_{so} \). The influence of these parameters on the outlet fluid pressure is because they enhance the hydrodynamic behavior of the fluid. Also, for the outlet temperature \( (T_{outlet}) \) of Fig. 5b, it is observed that the outlet temperature is mostly affected by the flowline inclination \( (\theta) \), afterward the superficial oil and water velocities \( (U_{so} \) & \( U_{sw}) \), the thermal conductivity of oil \( (\lambda_o) \), and wall heat flux \( (q^-) \) for an ST flow pattern system. The effect of the inclination angle, \( \theta \) on the variation of temperature is entrenched because \( \theta \) influences the flow regime and in turn determines the heat transfer. \( U_{sw} \) and \( U_{so} \) have a great influence on the fluid temperature positively since a slowly moving fluid retains heat. \( \lambda_o \) and the \( q^- \) are also positive on the outlet fluid temperature because they enhance the thermal behavior of the fluid. On the parameters’ combination, \( \theta U_{sw} \) are the most influencing interactions on the fluid temperature. \( \theta U_{so} \) has the most inverse influence on the outlet fluid temperature.

From the result of this analysis, the most important parameters affecting both outlet fluid pressure and temperature are mostly flowline inclination \( (\theta) \), superficial oil and water velocities \( (U_{so} \) & \( U_{sw}) \), the thermal conductivity of oil \( (\lambda_o) \), and the wall heat flux \( (q^-) \). This reaffirms two-phase heat transfer as dependent on the flowline inclinations, hydrodynamic, and thermal behavior of the flow. As seen below, the model can provide reasonable predictions of the hydrodynamic behavior of the oil-water flow, there is good accuracy for the prediction of flow pattern, pressure drop, liquid hold, and velocity distribution. In the following subsections, the effect of flowline inclinations on the hydrodynamic and thermal behaviors will be investigated deeply to ensure efficient crude oil transportation.

4.2. Effect of flowline inclinations on the hydrodynamic fluid behavior

4.2.1. Flow pattern and liquid fraction

- **Flow pattern**

Table 7 summarises the obtained flow patterns for different flowline inclinations \((-10^\circ, -4^\circ, 0^\circ, +4^\circ, +7^\circ, +10^\circ)\). For 60% input water cut, \( Re_{so} \) values of 450–3250 and \( Re_{sw} \) maintained at 6772, it is noticed that the change of flowline inclination angle leads to a change in the flow pattern transition boundaries from Po/o, ST & MI to Dw/o & o/w. Po/o is formed at low \( Re_{so} \) (≈450) and high \( Re_{sw} \) (6772) due to buoyant forces acting to settle the oil droplet, increasing the \( Re_{so} \) forms ST & MI with droplets at one or both sides of the interface observed, and a further increase in \( Re_{so} \) (≈2750) gives rise to Dw/o & o/w flow regime by the turbulent interfacial forces forcing droplets to spread all over the flowline. As seen in Table 6, for the horizontal situation the flow pattern of Dw/o & o/w was mostly noticed over a wider range of oil and water flow rates than for the downward and upward flowline inclinations. When the flowline was inclined from horizontal to upward inclinations of 4\(^\circ\) and 10\(^\circ\), the observed flow pattern was similar to horizontal flow except at \( Re_{so} \) of roughly 1280 where the flow pattern is ST & MI. This is due to a reduction in turbulence forces in ST & MI created by the gravitational forces which hinder the denser water phase leading to a high liquid holdup. As the flowline was inclined from horizontal to downward inclined positions 4\(^\circ\) and 10\(^\circ\), the flow pattern is observed to be mostly ST & MI with Po/o and Dw/o only observed respectively at low and high \( Re_{so} \). Varying the inclination angle downward reduces liquid holdup and the gravitational forces, which are most pronounced at upward inclinations and tend to decelerate the denser water phase in the upward direction. Water is the fastest-moving phase during the downward flow and it reduces the holdup.

- **Liquid holdup**

The input volume fractions may be different from the in-situ volume fractions and this behavior describes holdup. The liquid

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Minimum (10% below nominal)</th>
<th>Nominal value</th>
<th>Minimum (10% above nominal)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta )</td>
<td>-10</td>
<td>0</td>
<td>+10</td>
<td>deg</td>
</tr>
<tr>
<td>( U_{sw} )</td>
<td>0.090</td>
<td>0.100</td>
<td>0.110</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_{so} )</td>
<td>0.090</td>
<td>0.100</td>
<td>0.110</td>
<td>m/s</td>
</tr>
<tr>
<td>( \lambda_w )</td>
<td>0.538</td>
<td>0.598</td>
<td>0.658</td>
<td>w/(m.K)</td>
</tr>
<tr>
<td>( \lambda_o )</td>
<td>0.149</td>
<td>0.135</td>
<td>0.149</td>
<td>w/(m.K)</td>
</tr>
<tr>
<td>( q^- )</td>
<td>165333.333</td>
<td>183703.704</td>
<td>202074.074</td>
<td>w/(m².K)</td>
</tr>
</tbody>
</table>
holdup, HL is simply the fraction of a particular fluid present in the interval of a pipe, and its accurate determination is useful to calculate frictional pressure drop and volumetric flow rates. The HL contour at the flowline cross-section is expressed in Fig. 6 and it shows improvement after refining the mesh for flow having input water cut of 60%, Re \text{so} values of about 450–3700, and Re \text{sw} = 6772. In the figures, Po/w is observed at Re \text{so} of 450 with higher water HL than oil in the continuous water phase. SI & MI is noticed as Re \text{so} increases above 450 showing almost equal HL of oil and water in the continuous oil-water phases. At Re \text{so} lower than 2750, Dw/o & o/w flow regime is observed as the HL of water decreases during the transition which indicated that the dispersed water continuous flow moved much faster than the dispersed oil continuous phase. Additional increase in Re \text{so} to around 3700 results in Dw/o where HL of

![Fig. 5. Parameters affecting the (a) fluid pressure, and (b) fluid temperature for ST flow.](image)

<table>
<thead>
<tr>
<th>Flowline Inclination</th>
<th>$-10^\circ$</th>
<th>$-4^\circ$</th>
<th>$0^\circ$</th>
<th>$+4^\circ$</th>
<th>$+7^\circ$</th>
<th>$+10^\circ$</th>
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<tr>
<td>Po/w</td>
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<tr>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>Dw/o &amp; o/w</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
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<td>ST&amp;MI</td>
<td>ST&amp;MI</td>
<td>Dw/o &amp; o/w</td>
<td>Dw/o &amp; o/w</td>
<td>Dw/o &amp; o/w</td>
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</tbody>
</table>

Table 7

The oil-water flow patterns at different flowline inclinations.
water further reduces, which demonstrated that the dispersed water droplets moved faster than the continuous oil phase. It can be seen that the water droplet concentration increased towards the flowline midpoint where the velocity is highest. Lift forces were responsible for the increased droplet concentration at the midpoint.

Fig. 6a and b describe the liquid holdup for horizontal and inclined flowlines, it is observed as the superficial oil velocity increases at constant water velocity during a transition from Po/w to Dw/o, the in-situ water volume fraction decreases. The Po/w is seen to have a higher water fraction than oil in the continuous water phase with an HL ratio between oil and water to be 0.73 in horizontal flow, 0.92 for upward flow, and 0.80 in the downward flow. This is owing to the gravitational forces acting in the upward flow hindering the denser water phase and increasing the heavy phase HL. ST & MI is noticed at higher oil flow rates with both oil and water having continuous phases, where the HL ratio between oil and water is 0.67 in horizontal flow, 0.74 for inclined flows, and 0.63 in a downward flow. For high flow rates of dispersed oil flow, where Dw/o & o/w flow is observed to occur. HL ratio between oil and water continuous phases is 0.41 in horizontal flow, 0.50 for inclined flow, and 0.43 in a downward flow. Further increase in the dispersed continuous oil flow phase leads to Dw/o being observed. Dw/o has an HL ratio between oil and water of 0.33 in horizontal flow, 0.45 for inclined flows, and 0.36 in a downward flow.

Finally, in upward flow, the denser phase decelerates due to gravity forces which increases the heavy phase holdup. In contrast, the velocity of the denser phase in the downward flow increases resulting in a decreased holdup.

4.2.2. Pressure along the flowline

The value of the pressure gradient along the flowline length was investigated at 60% input water cut, with Re values of 450–3700 while maintaining Re values as shown in Fig. 7. It is observed in horizontal flow that the frictional pressure gradient increases in the transition from Po/w to Dw/o flow due to increased turbulence forces (Fig. 7a). Based on Po/w, when the inlet oil flow rate increases, the oil-water flow pattern transition to ST & MI. The pressure variation rose as the water continuous phase in Po/w was replaced with an oil-water continuous phase, which increases the wall friction and frictional pressure drop. Increasing the oil flow rates, the oil-water flow changes to Dw/o & o/w flow regime, and the pressure variation increases because of the high inlet velocity and the amount of continuous oil-water phases in the flowline. Based upon Dw/o & o/w, a further increase in the inlet oil flow rates, the oil-water flow changes to Dw/o. The pressure gradient further increases as the continuous oil-water phases are substituted with an oil continuous

![Diagram](image-url)
phase, which increases the frictional pressure drop. However, due to the influence of the hilly-terrain flowline as seen in this study in Fig. 7b and c. The frictional pressure gradients at the different flow transitions from Po/w to Dw/o are in general noticed to be lower than horizontal flow. This was attributed to a higher in-situ water fraction or holdup in the upward and reduced holdup in the downward flows. In essence, confirms the investigations that flow pattern has a big impact on the measured pressure gradient [32].

In summary, the frictional pressure drop in production flowlines has a huge impact on the operational cost and design. It restricts the maximum flow and hence a critical parameter, during production optimization and cost evaluation.

4.2.3. Velocity distribution

Fig. 8 shows the midpoint velocity contour of the oil-water phase in a fully developed two-phase flow for various Re_{so} while Re_{sw} is maintained at 6772 and an input water cut of 60%. It is observed that a pronounced velocity distribution effect is noticed in the water phase than in the oil phase. The velocity contour of the water phase is higher at the interface and near the flowline wall, this implies that the velocity gradient of the water phase is higher than the oil phase. It is also discovered that the oil-water two-phase velocity decelerates while approaching either the oil-water interface or due to impeding effects of fluid viscosity. The average velocities distribution of Po/w is 0.34 m/s (Figs. 8a), 0.40 m/s for SI & MI (Figs. 8b), 0.61 m/s for Dw/o & o/w in Figs. 8c, and 0.79 m/s for Dw/o (Fig. 8d).

4.3. Effect of flowline inclinations on thermal fluid behavior

4.3.1. Temperature distributions

The temperature distribution at the midpoint of the flowline cross-section for 60% input water cut and different inclinations are shown in Fig. 9. As can be seen in the temperature contour, the temperature of both oil and water phases increases because of the higher surrounding temperature through the constant wall heat flux and the convective heat transfer effects. Therefore, as the superficial oil velocity increases at constant water velocity during the transition from Po/w to Dw/o in horizontal flow, the temperature of oil and water keeps increasing from the flowline wall to the fluid interface, and the temperature gradient in the radial direction of the water phase is smaller than that of the oil phase gradient (Fig. 9a). This is because oil has a lower specific heat transfer heat capacity \(c_p\) than water and the phenomenon entails heat is transferred from the wall to the oil interface faster.

Fig. 9b and c explain the temperature variation along the inclined flowline cross-section. The temperature variation is observed to be higher than that of horizontal flow. This was ascribed to a higher liquid holdup by gravitational forces in the upward flow and a
reduced liquid holdup in the downward flow.

4.3.2. HTC

The numerical HTC results at 60% input water cut, different Re_{so} (about 450–3700), flow patterns, flowline inclinations (−10°, −4°, 0°, +4°, +10°), and Re_{sw} of 6772 are shown in Fig. 10. In downward flows, the flow pattern transition from Po/w to ST & MI regime causes a decrease in HTC values. Further increase in the oil flow rates coupled with gravity forces working in the reverse direction to the upward inclined flow enhances the interfacial mixing of the oil-water flow, resulting in increased overall HTC from ST & MI to Dw/o & o/w. Changing flowline inclination from horizontal to downward flow increases the HTC during flow pattern transition. However, the HTC for horizontal flow is higher than the downward flow at Re_{so} values of about 1200–1800. This difference is ascribable to Dw/o & o/w flow pattern observed in horizontal flow and ST & MI for the downward flow at this Re_{so} range. HTC is higher at this range for horizontal flow due to higher turbulence forces in Dw/o & o/w than in ST & MI flow pattern.

In the end, the proposed numerical model was able to compute the HTC results for two-phase oil-water flows and it is a function of the flow pattern.

5. Conclusions

A transient state 3-D non-isothermal two-phase oil-water flow model is established to investigate the mechanisms of flow behavior and heat transfer in different flowline inclinations. LRN k-e is utilized to simulate the turbulence viscosity based on the solution of the momentum conservation and energy conservation equations. The computed results were validated with experimental data in the literature with a relative error of within 3%. The model was further employed to ascertain the effect of input water cut and flowline inclinations on the flow regimes, and the results were validated in the literature, both cases demonstrating a high accuracy level of the models. Then, a study of oil-water simulations at different flow patterns and flowline inclinations is executed. Sensitivity analyses were initially carried out using the factorial design method on the model to determine the most relevant parameters of the hydrodynamic and thermal behaviors. Exhaustive flow information on flowline cross-sections at different flowline inclinations and flow patterns is investigated. The major conclusions of this work acquired are:

- The outlet flowline pressure for the stratified flow regime is mainly affected by the superficial oil velocity (U_{so}), followed by the parameter combination of U_{so} U_{sw}, and then superficial water velocity (U_{sw}). The flowline inclination (θ) has the most inverse influence on the outlet fluid pressure.
- The two-phase oil-water outlet temperature for the ST flow regime is largely affected by the flowline inclination (θ), afterward the superficial oil and water velocities (U_{so} & U_{sw}), and the thermal conductivity of oil (\lambda_{o}). On the parameters’ combination, θU_{sw} are the most influencing interactions on the fluid temperature, and θU_{so} has the most inverse influence on the outlet fluid temperature.
• In the horizontal flowline at 60% input water cut, the in-situ water volume fraction reduces as the oil superficial velocity increases at constant water superficial velocity during a transition from Po/w to Dw/o. For upward flow, the in-situ water volume fraction rises because the denser phase decelerates due to gravity forces. Contrarily, a reduced holdup in the downward flow results from a velocity rise in the denser phase.

• At 60% input water cut, the frictional pressure gradient in the horizontal flowline rises through the transition from Po/w to Dw/o flow. The pressure drops increased as the water continuous phase was replaced with an oil continuous phase, which increases the wall friction. The frictional pressure gradients in inclined flows reduce due to a higher in-situ water fraction or holdup.
• A noticeable velocity distribution effect is observed in the water phase than in the oil phase at 60% input water cut. The velocity contour of the water phase is higher at the interface and near the flowline wall which suggests that the velocity gradient of the water phase is higher than the oil phase.

• The HTC increases during the flow pattern transition by changing flowline inclination from horizontal to inclined flows at an input water cut of 60%. Nonetheless, the HTC for horizontal flow is higher than the inclined flows at Re<sub>50</sub> values of 1200–1800. This is due to higher turbulence forces in Dw/o & o/w than in ST & MI flow patterns in inclined flows.

Therefore, the numerical model we suggested could be widely applied to calculate the global fluid properties and other operating variables in the two-phase oil-water transportation system.

Author contributions

The following statements should be used “Conceptualization, Nsidibe Sunday, Khaled Chetehouna and Nicolas Gascoin.; methodology, Nsidibe Sunday, Abdelhakim Settar, Khaled Chetehouna, and Nicolas Gascoin.; software, Nsidibe Sunday; validation, Abdelhakim Settar, Khaled Chetohuna, and Nicolas Gascoin.; formal analysis, Nsidibe Sunday, Abdelhakim Settar, Khaled Chetehouna.; investigation, Abdelhakim Settar, Khaled Chetehouna.; resources, Nsidibe Sunday, Nicolas Gascoin.; data curation, Nsidibe Sunday, Nicolas Gascoin; writing—Nsidibe Sunday; writing—review and editing, Nsidibe Sunday, Abdelhakim Settar, Khaled Chetehouna, and Nicolas Gascoin.; supervision, Abdelhakim Settar, Khaled Chetehouna, Nicolas Gascoin.; project administration, Khaled Chetehouna, and Nicolas Gascoin.; funding.

All authors have read and agreed to the published version of the manuscript.”

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors express heartfelt appreciation to the Petroleum Technology Development Fund (PTDF), Nigeria for funding the Ph.D. thesis at PRISME Laboratory INS Center Val de Loire, Bourges- France.

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