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COB-2021-0357 INFLUENCE OF THERMAL EFFECTS IN STABILITY ANALYSIS FOR SEVERE SLUGGING

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Abstract. *In this paper a numerical study on the thermal effects at linear stability analysis for the multiphase flow of oil in a pipeline-riser system is presented. The developed model considers that the flow is one-dimensional and three-phase throughout the system. The liquid and gas phases are considered compressible. Furthermore, it is assumed that oil and water have the same speed and are homogenized. The flow pattern in the pipeline and riser is determined based on the local state variables and inclination angle. The characterization of fluids and the mass transfer between the phases done according to the black oil model while the void fraction depends on the flow pattern. The energy conservation equation is added in a methodology previously developed, in order to take into account the thermal coupling with the mass and momentum conservation equation. The equations were solved numerically using MATLAB software. The results achieved are according with isothermal analysis obtained using the same approach, although some deviations are observed. The eigenvalues largest real part calculated by the model that includes the thermal effects were higher than those obtained by the isothermal model. In both cases, the largest eigenvalue presents a positive real part, therefore the flow is unstable for the standard condition adopted, and consequently, there will be severe slugging. The difference between the largest eigenvalues real part is* $87.4\,\%$. *The deviations occurred due to the effect of temperature on the mass transfer (vaporization), compressibility, expansion, and the thermophysical properties of the phases. The results obtained highlight the potential of this technique, as being a very useful way of evaluate severe slugging in offshore oil production systems.*

Keywords: *linear stability analysis, three-phase flow, severe slugging, thermal effects, petroleum production technology.*

1. INTRODUCTION

Severe slugging is a phenomenon dominated by topography, characterized by the formation and cyclic production of long slugs of liquid and fast gas expulsion. This configuration can occur for low gas and liquid flows rates when a downward sloping section (flowline) is followed by another section with upward slope (riser). Flow instability results from the combination of two mechanisms that compete with each other: pressure drop along the riser (mainly due to the distribution of the void fraction) and compressibility of gas in the flowline (Lorimer and Ellison, 2000).

The main issues caused by severe slugging in offshore production systems were reported in Wordsworth *et al.* (1998): (a) high average backpressure at the wellhead (Wet Christmas Tree), promoting huge production losses, (b) high instantaneous flow rates, generating oscillations in the liquid control system in the separators in the platform and eventually shutdown, and (c) fluctuations in the flow in the reservoir. The different stages of the phenomenon of severe slugging can be seen in Taitel (1986) .

Most severe slugging studies were developed for vertical risers, where one-dimensional, isothermal flow is admitted and with an equation of linear momentum for the mixture in which only the gravitational term is considered. Furthermore, the fluids used in these systems are air and water at low pressures where the compressibility of the liquid phase and mass transfer between phases are neglected. Thus, the resulting models usually have many simplifications to capture the real behavior that occurs in oil production systems (Azevedo, 2017).

Thermal analysis is important in assuring minimum temperatures, to prevent hydrates and paraffin formations in the pipelines and risers. The incorporation of the energy equation and consequently of the thermal effects, aims to make the severe slugging model even more realistic. Reliable and simple models can generate several benefits for the industry and upgrade production planning. This study has the objective to implement numerically a model to evaluate severe slugging in offshore systems through linear stability theory, including the thermal effects along with the flow, and compared with the results found in a similar isothermal analysis.

2. Model

The model equations are based on Andreolli *et al.* (2018). It considers the flow as one-dimensional and three-phase throughout the system. The liquid and gas phases are considered compressible. Furthermore, it is assumed that oil and water have the same speed and are homogenized. The temperature drop in the two-phase flow (gas-liquid) is being evaluated. The flow pattern in the pipeline and riser is determined based on the local state variables and inclination angle. The characterization of fluids and the transfer of mass between the phases is done according to the black oil model. For boundary conditions, constant pressure at the separator at the platform and constant temperature at Wet Christmas Tree (WCT) were adopted.

2.1 System geometry

This work considers the general geometry of the production system shows in Figure 1 to formulate the balance equations. This geometry consists of a flowline connecting the WCT with the platform, located at the sea bed and water layer, through a variable path s. The local inclination angle θ depends on the local position. The origin of the coordinate system (x, z) is set at the WCT.

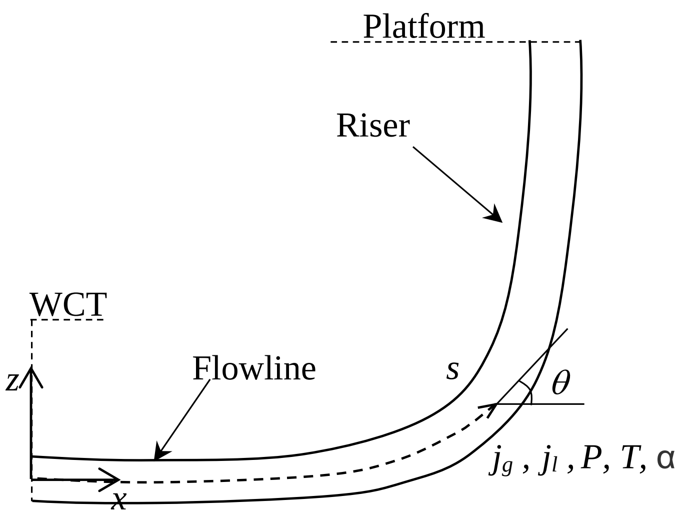

Figure 1. General geometry of the production system.

2.2 Conservation equations

The multiphase flow model adopted is based on the mixture model and considers four balance equations: mass conservation for the gas and liquid phases and simplified equations for linear momentum and energy conservation for the gas-liquid mixture. The mass balance equations for the gas and liquid phases have been adapted from Collier and Thome (1994):

$$\frac{\partial}{\partial t}(\rho_g \alpha) + \frac{\partial}{\partial s}(\rho_g j_g) = \Gamma \tag{1}$$

$$\frac{\partial}{\partial t}\left[\rho_l\,(1-\alpha)\right] + \frac{\partial}{\partial s}\,(\rho_l j_l) = -\Gamma \tag{2}$$

The black oil approach considers that the liquid phase has solubilized gas the vaporizes along the flow. Furthermore, the variables ρ_g and j_g represents the density and superficial velocity for gas, while ρ_l and j_l are the density and superficial velocity for liquid and α is the void fraction and t the time.

For most transients that happen in the segment of oil and gas, the system's response proves to be sufficiently slow. The pressure gradient is in general the sum of friction, gravitational and inertial contributions. However, flows are low in offshore systems, so pressure waves have no dominant effect compared to continuity waves. The linear momentum equation is modeled, according to the NPW (No Pressure Wave) model, in which the inertial terms are neglected (Masella *et al.*, 1998):

$$\frac{\partial P}{\partial s} = \left(\frac{\partial P}{\partial s}\right)_F - \rho\, g\, \sin\theta \tag{3}$$

$$\rho = \rho_g\,\alpha + \rho_o\,\alpha_o + \rho_w\,\alpha_w \tag{4}$$

$$\alpha + \alpha_o + \alpha_w = 1 \tag{5}$$

where $\left(\frac{\partial P}{\partial s}\right)_F$ is the frictional pressure drop, P is the pressure, ρ, ρ_o e ρ_w are, respectively, the density of the mixture, oil, and water, g represents the acceleration of gravity, while α_o and α_w are, respectively, the volumetric fractions of oil and water.

The energy conservation equation selected is based on Wallis (1969) and neglects axial heat flux, dissipative sources, and normal stress powers. Heat transfer to the walls is taken into account. To be consistent with the linear momentum conservation equation, the kinetic energy terms are also neglected:

$$\frac{q_0\,P_c}{A} + G\,g\,\sin\theta + \frac{\partial}{\partial t}\left[\alpha\,\rho_g\,\hat{u}_g + (1-\alpha)\,\rho_l\,\hat{u}_l\right] + \frac{\partial}{\partial s}\left[\rho_g\,j_g\,\hat{h}_g + \rho_l\,j_l\,\hat{h}_l\right] = 0 \tag{6}$$

$$G = \rho_g\,j_g + \rho_l\,j_l \tag{7}$$

where q_0 is the heat flux on inner walls of the duct, P_c the heated perimeter, G is total mass flux, given by Eq. (7), $\hat{u}_g$ and $\hat{h}_g$ are respectively the specific internal energy and enthalpy of gas, respectively, while $\hat{u}_l$ and $\hat{h}_l$ are the specific internal energy and enthalpy the liquid phase.

2.3 Closure laws

To close mathematically the problem, constitutive relations must be added.

2.3.1 Frictional pressure drop

The friction term in the linear momentum equation, Eq. (3), is modeled using the two-phase multiplier φ^2_{f0}, as presented by Wallis (1969), as being the ratio between the frictional pressure drop and the pressure drop $\left(\frac{\partial P}{\partial s}\right)_l$, considering that the total mass flux is composed only of liquid:

$$\varphi^2_{f0} = \frac{-\left(\frac{\partial P}{\partial s}\right)_F}{-\left(\frac{\partial P}{\partial s}\right)_l} \tag{8}$$

$$\left(-\frac{\partial P}{\partial s}\right)_l = \frac{1}{2}\,f_l\,\frac{G^2}{\rho_l\,D} \tag{9}$$

where f_l is the Darcy friction factor for the liquid phase and D is the pipe inner diameter. Thus, Eq. (3) becomes:

$$\frac{\partial P}{\partial s} + \varphi^2_{f0}\,\frac{1}{2}\,f_l\,\frac{G^2}{\rho_l\,D} + \rho\,g\,\sin\theta = 0 \tag{10}$$

Different correlations can be used in this approach. In this study, the correlation presented in Ishii and Hibiki (2006) is adopted to determine the homogeneous two-phase multiplier φ^2_{f0}.

2.3.2 Void fraction

In order to determine the void fraction it was assumed that there is an algebraic relation between the void fraction and the local flow conditions:

$$\alpha = \alpha\left(j_g,\, j_l,\, P,\, T,\, \theta\right) \tag{11}$$

where T is the local temperature.

Equation (11) allows the application of many empirical correlations to estimate the void fraction, especially the correlations based on the drift flux model, proposed by Zuber and Findlay (1965). The stratified and intermittent flow patterns for different inclination angles are frequent in offshore systems, then specific correlations should be used. When the flow pattern is stratified, an approach (Taitel and Dukler, 1976) based on local equilibrium condition were selected, while when the flow pattern is intermittent, the void fraction correlation of Bendkisen (1984) is considered.

2.3.3 Heat flux

Heat transfer is modeled through an overall thermal conductance, made of internal convective heat transfer through the fluid, conduction at the different wall layers, and external natural convection heat transfer through the seawater. Thermal capacitance is neglected. The term related to inner heat flux in the Eq. (6) is determined as follows:

$$q_0 = \frac{q'}{2\,\pi\,r_{int}} \tag{12}$$

$$q' = U A\,(T - T_{sw}) \tag{13}$$

$$UA = \frac{2\,\pi}{\dfrac{1}{r_{int}\,h_{int}} + \dfrac{\ln\left(\dfrac{r_{ext}}{r_{int}}\right)}{\kappa_{eff}} + \dfrac{1}{r_{ext}\,h_{ext}}} \tag{14}$$

$$\kappa_{eff} = \frac{\ln\left(\dfrac{r_{ext}}{r_{int}}\right)}{\sum_1^{N-1} \dfrac{\ln\left(\dfrac{r_{i+1}}{r_i}\right)}{\kappa_i}} \tag{15}$$

where T_{sw} represents the temperature of the seawater on the outer side, while r_{int} and r_{ext} are respectively the inner and outer radii, UA is the overall thermal conductance, κ_{eff} is the equivalent thermal conductivity of the diferent flowline layers and q' is the thermal power per unit length.

Radiation heat transfer is neglected in the determination of the global heat transfer coefficient UA since this process is relevant only at high temperatures. The heat transfer coefficient for forced convection at the inner side h_{int} depends on the flow pattern. Given these considerations, the correlation of Tang and Ghajar (2007) is adopted. To calculate the convective coefficient at the outer side h_{ext}, the Nusselt number correlation available in Churchill and Chu (1975) for single-phase free convection in long and inclined cylinders is considered.

2.3.4 Fluid characterization

According to McCain (1990), oil can be characterized by a compositional model, which considers different components, or through the approximation known as the black oil model, which defines oil as being composed of a liquid and gas phases, with the same composition.

Oil is composed of several components, through numerous branches leading to a large combination of compounds so that it can be inferred that there are no two equal oils. Therefore, modeling through the components that make up the mixture that forms the oil is very complex (Danielson, 2003).

The black oil model is widely applied to industry, with satisfactory results, especially for heavier oils were the chromatographic analysis does not provide information on most components.

In this paper, the black-oil model is adopted for the characterization of fluids. The black-oil approach considers the existence of two components in the mixture, liquid, and gas. For a specific condition (P, T) the black-oil model admits that the liquid phase contains dissolved gas, and when this phase is stabilized in the standard condition (SC), a liquid phase is separated into gas and liquid.

The set of input variables that characterize the fluids are: the standard densities of oil, gas, and water, represented respectively by ρ_{o0}, ρ_{g0} and ρ_{w0}, gas-oil ratio GOR and water-oil ratio WOR.

The densities of oil, gas, water, and liquid under local pressure and temperature conditions are calculated by:

$$\rho_o = \frac{\rho_{o0} + \rho_{g0}\, R_{so}}{B_o} \tag{16}$$

$$\rho_g = \frac{\rho_{g0}}{B_g} \tag{17}$$

$$\rho_w = \frac{\rho_{w0}}{B_w} \tag{18}$$

$$\rho_l = \frac{\rho_{l0} + \rho_{g0}\, R_{sl}}{B_l} \tag{19}$$

where $B_o\,(P,\,T)$, $B_g\,(P,\,T)$, $B_w\,(P,\,T)$ and $B_l\,(P,\,T)$ are the formation volume factors of oil, gas, water and liquid, respectively, while $R_{so}\,(P,\,T)$ and $R_{sl}\,(P,\,T)$ are respectively the gas-oil and gas-liquid solubility ratios. Several black oil correlations can be used to calculate these variables as a function of pressure, temperature and oil API grade.

2.3.5 Mass transfer term

The mass transfer model adopted is the one developed in Nemoto and Baliño (2012), in which the black oil approach was considered. With the assumption that mass transfer occurs, due to changes in gas solubility, as the oil flows with speed $u_o = u_l = \frac{j_l}{1-\alpha}$, the mass transfer term between the phases can be expressed by:

$$\Gamma = -\rho_{g0}\, j_{l0} \left(\frac{1-\alpha}{j_l} \frac{\partial R_{sl}}{\partial t} + \frac{\partial R_{sl}}{\partial s} \right) \tag{20}$$

where j_{l0} is the mean liquid superficial velocity at standard condition.

2.4 Boundary conditions

In order to solve the partial differential equations that govern the problem, it is necessary to define the boundary conditions and the initial conditions.

At the final node of the system (downstream node) is the production separator $(s = s_t)$. For this node, constant pressure is defined:

$$P\,(s_t,\, t) = P_s \tag{21}$$

At the initial node of the system (the most upstream node) is the WCT $(s = 0)$. For this node a constant temperature is established:

$$T\,(0,\, t) = T_{WCT} \tag{22}$$

Furthermore, for the initial node, it was assumed a condition of constant mass flow of the oil and gas phases. For water, there is no mass transfer, while for the oil and gas phases, the limit condition for the velocities superficial is compatible with a flash test under local conditions at the WCT:

$$j_g\,(0,\, t) = \frac{GOR - R_{so}}{1 + WOR}\, B_g\, j_{l0} \tag{23}$$

$$j_o\left(0,\,t\right) = \frac{B_o}{1+WOR}\,j_{l0} \tag{24}$$

$$j_w\left(0,\,t\right) = \frac{WOR}{1+WOR}\,B_w\,j_{l0} \tag{25}$$

The superficial velocity of the liquid is given by:

$$j_l\left(0,\,t\right) = j_o\left(0,\,t\right) + j_w\left(0,\,t\right) = \frac{B_o+WOR}{1+WOR}\,B_w\,j_{l0} \tag{26}$$

The inlet local pressure is obtained integrating Eq. (10), so:

$$P\left(0,\,t\right) = P_s - \int_0^s \left(\frac{\partial P}{\partial s}\right) ds \tag{27}$$

The outlet local temperature is calculated through the integration of Eq. (6), resulting in:

$$T\left(s_t,\,t\right) = T_{WCT} + \int_0^s \left(\frac{\partial T}{\partial s}\right) ds \tag{28}$$

2.5 Stationary state

The stationary state can be obtained by setting to zero the time derivatives in the dynamic equations. Variables at stationary state are denoted with superscript $\sim$. Then, the following equations must be solved simultaneously:

$$\tilde{j}_g = \frac{GOR-\tilde{R}_{so}}{1+WOR}\,\tilde{B}_g\,j_{l0} \tag{29}$$

$$\tilde{j}_o = \frac{\tilde{B}_o}{1+WOR}\,j_{l0} \tag{30}$$

$$\tilde{j}_w = \frac{WOR}{1+WOR}\,\tilde{B}_w\,j_{l0} \tag{31}$$

The superficial velocity of the liquid can be written as:

$$\tilde{j}_l = \tilde{j}_o + \tilde{j}_w = \frac{\tilde{B}_o+WOR}{1+WOR}\,\tilde{B}_w\,j_{l0} \tag{32}$$

Integrating Eq. (10) local pressure is calculated along the system as:

$$\tilde{P} = P_s - \int_0^s \widetilde{\left(\frac{\partial P}{\partial s}\right)} ds \tag{33}$$

The local temperature through with the system is found by integration of Eq. (6), resulting in:

$$\tilde{T} = T_{WCT} + \int_0^s \widetilde{\left(\frac{\partial T}{\partial s}\right)} ds \tag{34}$$

Void fraction, liquid and gas density, and any other dependent variable are calculated from the corresponding relations evaluated at the stationary condition.

2.6 Perturbed dynamic equations

Transient multiphase one-dimensional flow models can be expressed in matrix form, as follows:

$$\{A\} + \underline{B} \cdot \left\{ \frac{\partial v}{\partial t} \right\} + \underline{C} \cdot \left\{ \frac{\partial v}{\partial s} \right\} = \{0\} \tag{35}$$

The vector of state variables is defined as:

$$\{v\} = \left\{ \begin{array}{cccc} j_g & j_l & P & T \end{array} \right\}^T \tag{36}$$

From this methodology, the mass conservation equations for liquid and gas phases can be rewritten, respectively as:

$$B_{21} \frac{\partial j_g}{\partial t} + B_{22} \frac{\partial j_l}{\partial t} + B_{23} \frac{\partial P}{\partial t} + B_{24} \frac{\partial T}{\partial t} + C_{21} \frac{\partial j_g}{\partial s} + C_{23} \frac{\partial P}{\partial s} + C_{24} \frac{\partial T}{\partial s} = 0 \tag{37}$$

$$B_{11} \frac{\partial j_g}{\partial t} + B_{12} \frac{\partial j_l}{\partial t} + B_{13} \frac{\partial P}{\partial t} + B_{14} \frac{\partial T}{\partial t} + C_{12} \frac{\partial j_g}{\partial s} + C_{13} \frac{\partial P}{\partial s} + C_{14} \frac{\partial T}{\partial s} = 0 \tag{38}$$

The linear momentum conservation equation, Eq. (3), in a simplified form is given by:

$$A_{31} + C_{33} \frac{\partial P}{\partial s} = 0 \tag{39}$$

For the energy conservation equation, Eq. (6), taking into account the algebraic relation between void fraction and the rest of the states variables and thermophysical properties, we can write:

$$A_{41} + B_{41} \frac{\partial j_g}{\partial t} + B_{42} \frac{\partial j_l}{\partial t} + B_{43} \frac{\partial P}{\partial t} + B_{44} \frac{\partial T}{\partial t} + C_{41} \frac{\partial j_g}{\partial s} + C_{42} \frac{\partial j_l}{\partial s} + C_{43} \frac{\partial P}{\partial s} + C_{44} \frac{\partial T}{\partial s} = 0 \tag{40}$$

The linear stability analysis consists of applying an infinitesimal perturbation in the equations that govern the problem and then linearizing them around the stationary state. Disregarding second order terms in perturbations, the system of perturbed dynamic equations can be written as:

$$\underline{\tilde{A}} \cdot \{\hat{v}\} + \underline{\tilde{B}} \cdot \left\{ \frac{\partial \hat{v}}{\partial t} \right\} + \underline{\tilde{C}} \cdot \left\{ \frac{\partial \hat{v}}{\partial s} \right\} = \{0\} \tag{41}$$

$$\{\hat{v}\} = \{\tilde{v}\,(s)\} + \{\hat{v}\,(s,\,t)\} \tag{42}$$

where the vector of perturbed variables $\{\hat{v}\}$ (size 4) and the square matrices of constant coefficients $\underline{\tilde{A}}$, $\underline{\tilde{B}}$, and $\underline{\tilde{C}}$ (size 4×4) are given by:

$$\tilde{A}_{ij} = \left(\frac{\partial A_i}{\partial v_j} + \sum_k \frac{\partial C_{ik}}{\partial v_j} \frac{\partial v_k}{\partial s} \right)^{\tilde{}} \tag{43}$$

$$\tilde{B}_{ij} = \left(B_{ij} \right)^{\tilde{}} \tag{44}$$

$$\tilde{C}_{ij} = \left(C_{ij} \right)^{\tilde{}} \tag{45}$$

2.7 Discretization

The pipe length is discretized in N nodes and the Eq. (41) is integrated in the range $s_i \le s \le s_{i+1}$. Representative values for any ϕ function or any variable within the integration interval is calculated through the average value between the adjacent nodes:

$$\phi_{i+\frac{1}{2}} \approx \frac{1}{2}\left[\phi\left(\tilde{v}_i\right) + \phi\left(\tilde{v}_{i+1}\right)\right] \tag{46}$$

$$\hat{v}_{i+\frac{1}{2}} \approx \frac{1}{2}\left(\hat{v}_i + \hat{v}_{i+1}\right) \tag{47}$$

Spatial and temporal derivatives are approximated by the finite difference method:

$$\left(\frac{\partial \hat{v}}{\partial s}\right)_{i+\frac{1}{2}} \approx \frac{\left(\hat{v}_{i+1} - \hat{v}_i\right)}{\Delta\, s_i} \tag{48}$$

$$\left(\frac{\partial \hat{v}}{\partial t}\right)_{i+\frac{1}{2}} \approx \frac{1}{2}\left(\frac{d\hat{v}_i}{dt} + \frac{d\hat{v}_{i+1}}{dt}\right) \tag{49}$$

2.8 Eigenvalue spectrum and stability criteria

Discretizing and integrating the perturbed equations about the position and including four additional lines corresponding to the boundary conditions, the following discrete system in matrix notation is obtained:

$$\underline{G^*} \cdot \left\{\frac{\partial \underline{\hat{v}}}{\partial t}\right\} + \underline{H^*} \cdot \{\underline{\hat{v}}\} = \{\underline{0}\} \tag{50}$$

$$\{\underline{\hat{v}}\}_j = \begin{cases} \hat{j}_{g\,j} & 1 \le j \le N \\ \hat{j}_{l\,j-N} & N+1 \le j \le 2\,N \\ \hat{P}_{j-2\,N} & 2\,N+1 \le j \le 3\,N \\ \hat{T}_{j-3\,N} & 3\,N+1 \le j \le 4\,N \end{cases} \tag{51}$$

where $\underline{G^*}$ and $\underline{H^*}$ are square matrices (size $4\,N \times 4\,N$), which are functions of the nodal values of the stationary solution, and $\underline{\hat{v}}$ (size $4\,N$) is the vector of perturbations of the state variables. The following transformation is applied to the system:

$$\{\underline{\hat{v}}\} = \{\underline{\hat{r}}\}\, \exp\left(\lambda\, t\right) \tag{52}$$

In Eq. (52) the parameters λ and $\{\underline{\hat{r}}\}$ represent respectively the set of eigenvalues and the associated nodal eigenvectors. From Eq. (50) and (52) it is found that:

$$\left(\lambda\, \underline{G^*} + \underline{H^*}\right) \cdot \{\underline{\hat{r}}\} = \{\underline{0}\} \tag{53}$$

The transformation expressed by the Eq. (52) transforms Eq. (50) in a generalized eigenvalues problem. Thus, Eq. (53) has a non-trivial solution when it satisfies the characteristic equation:

$$\det\left(\lambda\, \underline{G^*} + \underline{H^*}\right) = 0 \tag{54}$$

The flow stability judgment is made by analyzing the eigenvalue spectrum λ. If there is any eigenvalue with a positive real part, the perturbations will amplify and the system will be unstable. If all eigenvalues present a negative real part, the disturbances will be dampened and the system will be stable.

3. Results and discussion

The analysis is being performed and the results are still preliminary. In Figure 2 is presented the spectrum of eigenvalues obtained through computer simulations, for evaluate of severe slugging in an offshore pipeline-catenary riser, with input parameters shown in 1.

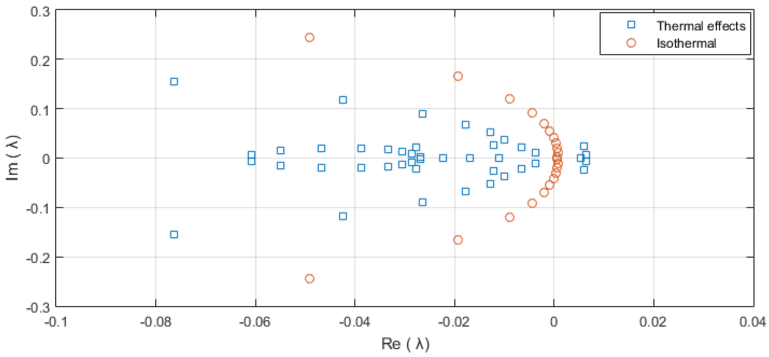

Figure 2. Eigenvalues behavior obtained through the parameters from Table 1.

Table 1. General input parameters for the simulations.

Symbol	Variable	Value
γ_{API}	^{o}API	19
γ_{g0}	Gas specific gravity	0.6602
j_{o0}	Superficial velocity for oil in standard condition	$0.5\,m/s$
j_{g0}	Superficial velocity for gas in standard condition	$50\,m/s$
ρ_w	Water density	$999.014\,kg/m^3$
T_{WCT}	Temperature at the WCT	$323.15\,K$
ε	Roughness	$4.5\times10^{-5}\,m$
P_s	Pressure at the separator	$25\,bar$
ρ_{sw}	Seawater density	$1024\,kg/m^3$
T_{sw}	Temperature of the seawater	$277.15\,K$
GOR	Gas-oil ratio	$145\,sm^3/sm^3$
WOR	Water-oil ratio	30%
D	Inner diameter	$0.1524\,m$
D_{ext}	Outside diameter	$0.3693\,m$
κ_{eff}	Effective thermal conductivity	$2.7808\,W/(m\ K)$
N	Number of nodes	25
L	Pipeline length	$1000\,m$
β	Pipeline inclination angle	2^{o}
X_r	Horizontal length of the top of the riser	$845\,m$
Z_r	Height of the top of the riser	$1300\,m$

The results achieved are according with isothermal analysis, obtained using the same approach, similar to those carried out by Andreolli *et al.* (2018). However, some deviations are observed. The eigenvalues calculated by the model that includes the thermal effects were higher than those obtained by the isothermal model. In both cases, the largest eigenvalue presents a positive real part, therefore the flow is unstable for the standard condition adopted, and consequently, there will be severe slugging. The difference between the largest eigenvalues real part is $87.4\,\%$. The deviations occurred due to the effect of temperature on the mass transfer (vaporization), compressibility, expansion, and the thermophysical properties of the phases. Furthermore, for any value constant of the superficial velocity of oil in an unstable region as it increases the superficial velocity of the gas, the eigenvalues spectrum moves in the direction of the boundary with the stable region.

4. Conclusions

In this paper was studied the severe slugging for a pipeline-riser system, including the thermal effects in the linear stability theory approach. The behavior of eigenvalues largest part real obtained with the thermal effects is compared to the similar isothermal analysis, showing an excellent agreement. However, deviations about the isothermal model must be taken into account in order to improve the reliability of numerical results and better production planning. This work shows the potential of this methodology, as being a very useful way to construct the eigenvalues spectrum for analysis of severe slugging, and promote flow assurance in offshore systems. The continuity of this work will be present stability maps and compared with field data on the next works from authors.

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