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A STUDY ON SLUG INDUCED STRESSES USING FILE-BASED COUPLING TECHNIQUE

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ABSTRACT

Cyclic stresses imposed on the piping system are the potential cause of severe fatigue damage and failure. These stresses are induced due to pressure fluctuations which occurred as result of the slug flow motion inside the pipe. In this study, a coupled Fluid-Structure Interaction approach based on file coupling technique between the CFD code for the flow domain and the Finite Element Analysis code for the structure domain was utilized to address the induced stresses on the structural pipe. Three cases of air-water have been investigated and the CFD results reveal that the slug frequency and slug velocity increased with increasing the water velocity while the slug length decreased with increasing the water velocity. On the other hand, the maximum principal stresses increased by 10.2% and 23.7% when the slug velocity increased from 2.26 m/s to 3.39 m/s respectively.

Keywords: fluid structure interaction, file based coupling, slug flow, stress analysis, horizontal pipe.

INTRODUCTION

The sudden failures for the structural components in several industries such as oil and gas, and nuclear power plant have shed the light on the investigation of the Fluid-Structure Interaction (FSI) phenomenon for these structures during the design stage. Internal two-phase flow interaction with the pipe in the production lines is an example of the FSI, in which, the fluid momentum and forces are transferred to the pipe wall and inversely the structure deformation in the form of displacement is transferred back to the fluid domain. Therefore, FSI in general is classified into one-way coupling (weak coupling) and two-way coupling (strong coupling) [1, 2]. In the strong coupling method, the entire fluid and solid domains variables are solved simultaneously in the same time step within one control equation. While, in the weak coupling method, the control equations of the fluid and solid domains are solved separately and the data between the two domains is exchange at each time step. File-based coupling technique is a sort of weak coupling, in which, the data transferred between the two domains using the input files to both CFD and FEA software.

Slug flow is a prevalent multiphase flow regime, in which, bulks of liquids separated by elongated gas bubble travel along the pipe. Great attention have been taken toward this flow regime because it potentially create large pressure surges, liquid carry-over or gas carry-under, and consequently it may induce vibration and reduce the pipe fatigue life. Bai and Qiang [3] classified the slug into three categories: operationally induced surges, terrain generated slugs, and hydrodynamic slugs.

The hydrodynamic slug is the likely slug type that may occur in the horizontal pipe due to its geometry and operation conditions. Hydrodynamic slugging is usually occurred when the waves at the interface between the two-phase (air/water) develop via a classical Kelvin-Helmotz instability and fill the whole pipe cross section [4]. Due to wall friction, the water velocity decrease and the pressure increase, then the water height increased. In contrary, the air flow cross section area decreased, thus, the air velocity increased. This velocity difference between the two-phases become extremely high and the hydrodynamic air force become higher than the surface tension, consequently, it lifts the interface and form waves, these waves develop and generate liquid slugs. These slugs block the air from passing through liquid slugs; accordingly, the air pushes the liquid slugs along the pipe and entrains small bubbles as shown in Figure-1.

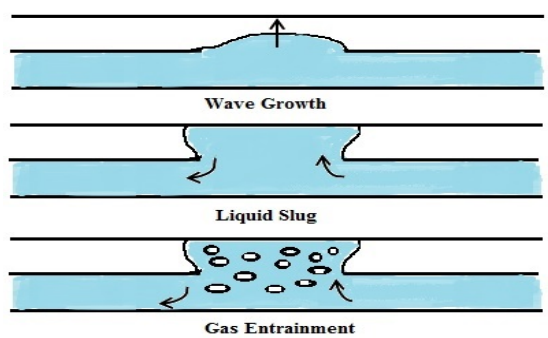

Figure-1. Hydrodynamic basis of slug formation.

Several approaches have been utilized for investigating the effect of the slug flow on the structural pipelines such as conventional method [5-8], in which, the slug is simulated by a moving mass or force on a beam element. However, this method simplify the problem and provides an acceptable insight of the slug effects but it neglect the real characteristics of the slug flow and presumed that the liquid slugs have similar length, velocity, and frequency which did not represent the real scenario. Recently, after the numerical simulation revolution, the trend was moved toward FSI coupling analysis in order to consider the effect of the slug characteristics on the structural components. Chica [9, 10] investigated the slug effect on the subsea jumper using two-way FSI coupling between the CFD for the fluid

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domain and FEA for the structural domain. Chica recommended that further investigation in term of modifying the flow boundary conditions is required for providing clear results for the effect of the slug flow on the structural fatigue life.

Due to unsteadiness and the turbulent mixing on the slug flow regime, pressure fluctuations raised in the fluid, which, subsequently, cause cyclic stresses in the pipe. The induced stresses due to these pressure fluctuations may eventually cause structural fatigue damage and reduce the total life time.

Therefore, this study aims to investigate the effect of slug flow on the structural pipe using FSI file-based coupling to evaluate the pressure fluctuation and the cyclic stresses in a horizontal pipe. First, the transient unsteady slug flow was modeled on the CFD software (Star-CCM+) to compute the induced pressure. Then, the computed transient pressure on the inner pipe wall was mapped to the nearest corresponding FE nodes. Second, the mapped CFD results were transferred to the FEA code (Abaqus) for conducting the stress analysis on the structural pipe.

NUMERICAL METHOD

a) File based coupling technique

Based on one-way and two-way coupling principle, a powerful links were established between Star-CCM+ (Finite Volume Analysis-FVA) for the fluid domain and ABAQUS (Finite Element Analysis-FEA) software for the solid domain. In file-based coupling, data is exchanged manually via files stored in the computer disk and the coupling steps at the interface are fully controlled by the user. Additionally, the coupling can also be automated using Java script code [11]. Figure-2 illustrates the adopted simulation scheme in this study.

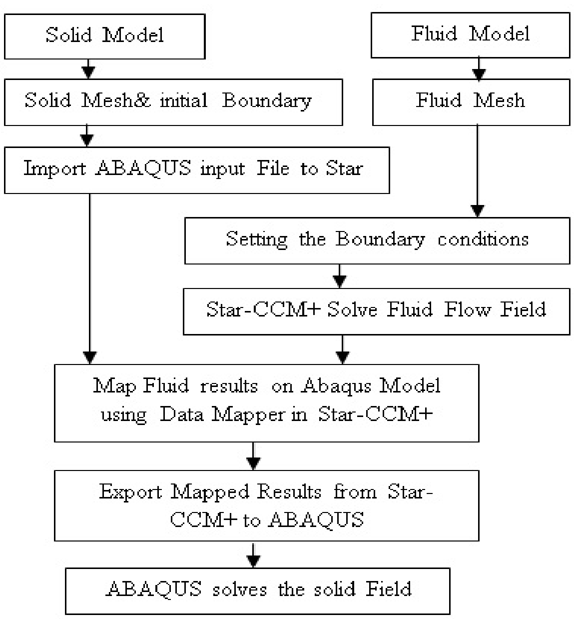

Figure-2. Schematic of file-based coupling technique.

b) CFD and FEA model

The CFD geometry was discretized using hexahedral elements (butterfly mesh) that are distributed along the length of the pipe as shown in Figure-3a. Mesh independent analysis was performed to obtain the trade-off between the computational accuracy and cost. Based on this study, a total of 134400 cells for the entire pipe were selected as an optimum element number.

In Star CCM+, the following physical model was specified: three dimensional, implicit unsteady, Eulerian multiphase, Volume of Fluid (VOF), segregated flow, k - ω turbulence, all y + treatment, gravity.

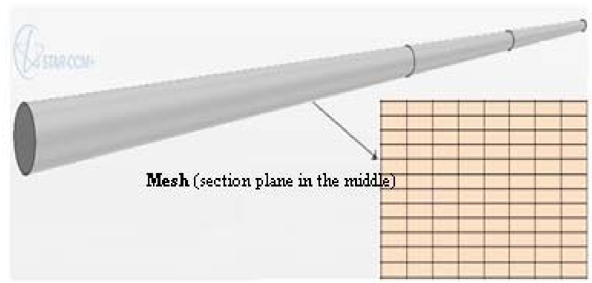

Figure-2a. Fluid geometry and mesh from Star-CCM+.

The FEA geometry was discretized into small continuum shell elements which are 3D stress/ displacement elements that are generally used in modeling the cylindrical structures. SC8R element with 8-nodes hexahedron and finite membrane strains was used to discretize the solid domain as shown in Figure-3b. A total of 4975 cells for the entire solid pipe were selected as an optimum element number.

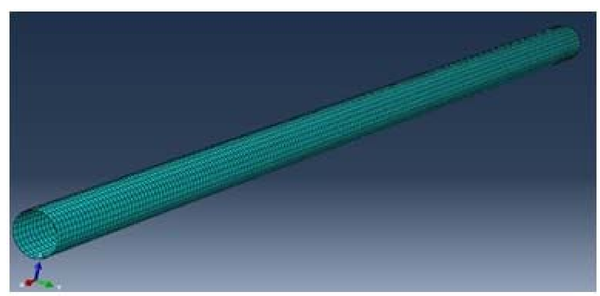

Figure-3b. Solid pipe mesh from abaqus.

In ABAQUS, the following physical model was specified: three dimensional, dynamic implicit step, and gravity.

c) Operation parameters and boundary conditions

For the fluid domain, air and water were used as the operating fluid. The physical properties for both fluids are illustrated in Table-1. Velocity inlet, pressure outlet, and FSI wall surface are the selected types of the boundary conditions in Star-CCM+. Three cases have been investigated in this study in order to address the effect of the slug parameters on the structural stresses as shown in Table-2.

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Table-1. Physical properties for air and water [11].

Property	Unit	Air	Water
ρ	kg/m³	1.185	997
μ	cP	0.01831	0.8899
σ	N/m	-	0.074

Table-2. The superficial velocities for the selected cases.

Case	Unit	Superficial water velocity	Superficial air velocity
1	(m/s)	1	2.443
2	(m/s)	0.86	2.443
3	(m/s)	0.698	2.443

For the solid domain, carbon steel pipe was used; the physical properties are presented in Table-3. Fixed support was selected for both pipe ends. FSI interface surface was specified in ABAQUS as well as in Star-CCM+ for the data mapping process.

Table-3. Physical properties for the carbon steel.

Property	Unit	Value
Density	kg/m³	7800
Young Modulus	GPa	206.8
Poisson Ratio	-	0.285

RESULTS AND DISCUSSIONS

a) Benchmark

In order to clearly address the consequences of the induced stresses due to slug flow regime. This study began with the stress analysis for single phase flow (water) with superficial velocity V_{SL}= 0.86m/s. same file based coupling technique was used in this benchmark. Figure-4 illustrates the induced stresses due to single phase water flow. It was observed that the maximum principal stress (σ_{max}) is equal to 1.82 MPa.

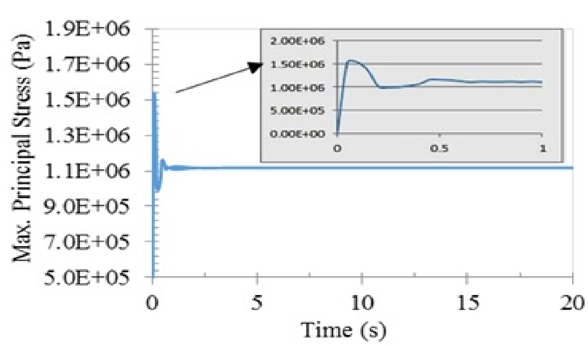

Figure-4. Maximum stress for single phase water flow.

b) Slug characteristics

The slug characteristics particularly the slug frequency (f_S), the slug length (L_S), and the slug transition velocity (V_S) was computed to characterize the slug phenomenon in the first stage, then these characteristics were correlated against the induced stresses. Figure-5 illustrates the slug frequency for the aforementioned cases; the frequency is presented as a function of the superficial water velocity. However, it was observed there is a proportional relation between the slug frequency and water velocity as shown in Figure-5. The obtained frequency was compared against Fetter [12] correlation which is computed by

$$f_s = 0.0175 . Fr_{Fet}^{1.37} \tag{1}$$

Where,

$$Fr_{Fet} = \frac{v_{SL}}{gD}\left[\frac{21.3 + v_m^2}{v_m}\right]$$

Where, D: Pipe diameter, V_m: mixture velocity

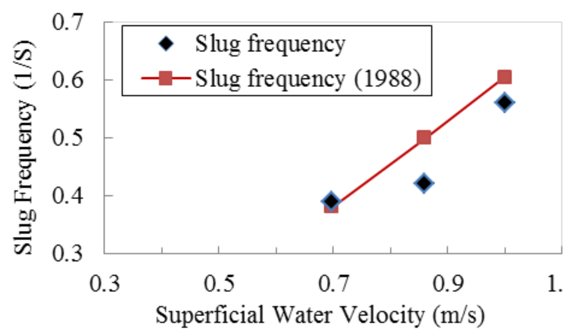

Figure-5. Slug frequency.

For the slug length, it was observed that when the water velocity increased the slug length decreased, thus there is an inverse relation between the slug length and the superficial liquid velocity as presented in Figure-6.

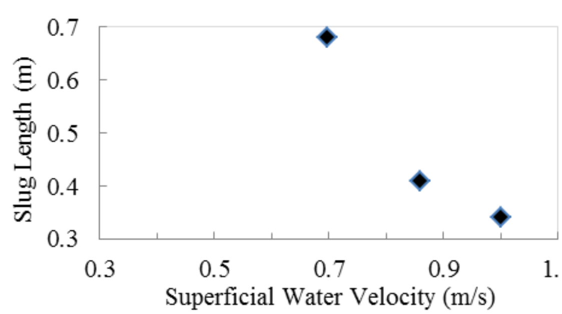

Figure-6. Slug length.

Generally, the slug velocity defined as a function of the drift velocity and the mixture velocity (V_m= V_{SL} + V_{SG}), thus when the mixture velocity increased the slug translation velocity was also increased. Figure-7 illustrates

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the slug translation velocity for the entire cases. Additionally, the slug velocity was compared against Gregory and Scott correlation [13] which illustrated by:

$$V_S = 1.35\ V_m \quad (2)$$

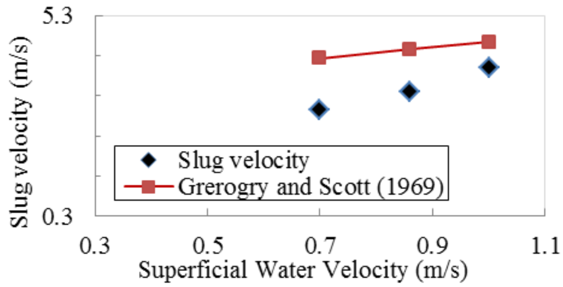
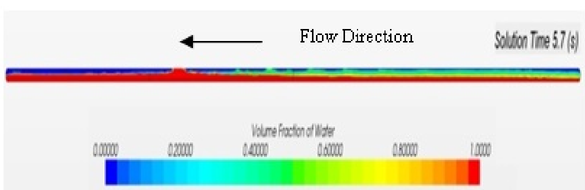


Figure-7. Slug translational velocity.

The slug was initiated for case-3 at x=5.2 m from the inlet section and it continued to grow along the pipe at the downstream sections as shown in Figure-8.



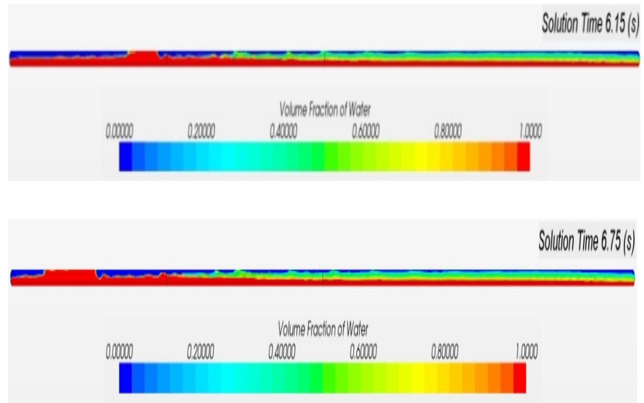
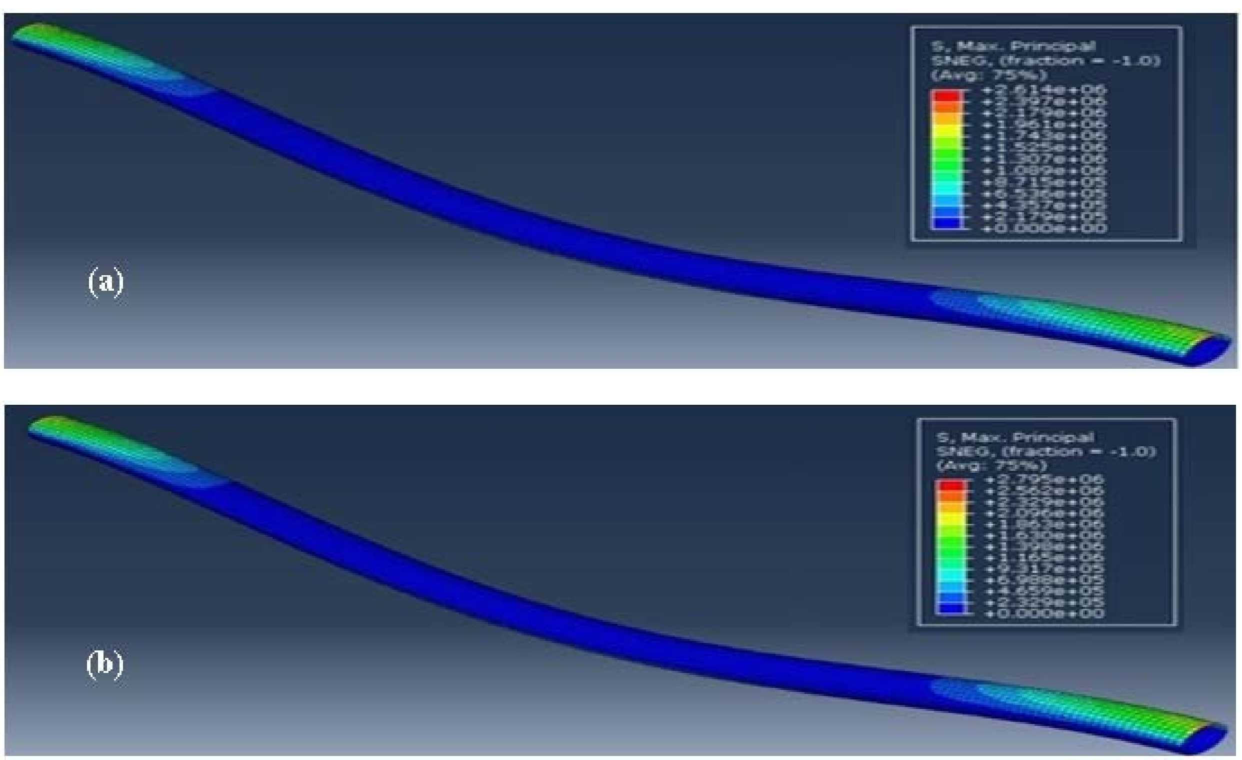


Figure-8. Slug initiation and growth for case-3.

c) Stress analysis

In this study, Maximum principal stress was utilized to address the slug effect on the solid pipe. The stress analysis has been conducted in Abaqus. Figure-9 illustrates the maximum principal stresses with the pipe deformation. The presented deformation was magnified 17 times.

Comparing the induced stresses due to slug flow and stresses due to water single phase flow, the material behaviour or response was observed same for both single and two-phase flows. However, for the same water velocity, the maximum induced stress σ_{max} due to slug in case-2 is 2.71 higher than the induced stresses due to water flow.



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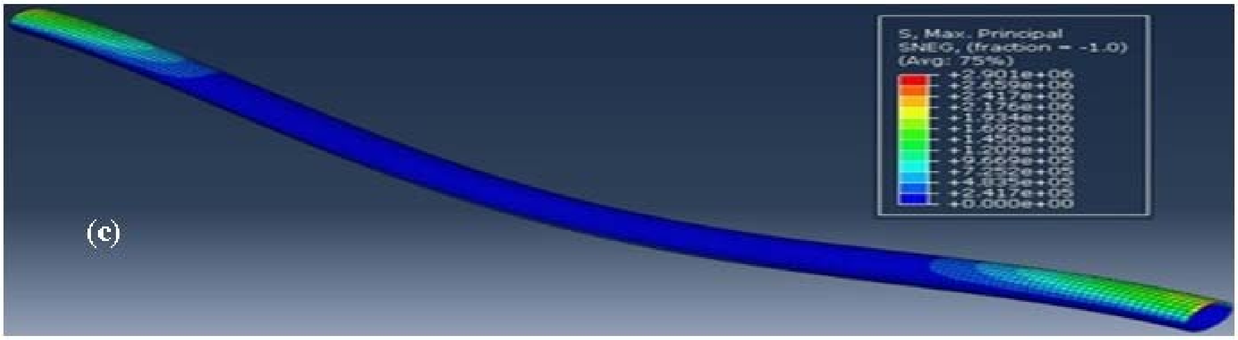

Figure-9. Maximum principal stress for a) cases-1 b) cases-2 c) cases-3.

Figure-10a, b, and c illustrate the stress load history for the three cases. In general, it was observed that there were abrupt jump in the stress at the first second from applying the load, and then the stress value was fluctuated within small range. This occurred as the result of the sudden energy conveyed to the pipe in the form of slug. While when V_{SL} = 0.86 m/s the maximum induced stresses is increased by 10.2% from V_{SL}=0.698 m/s as shown in Figure-10b.

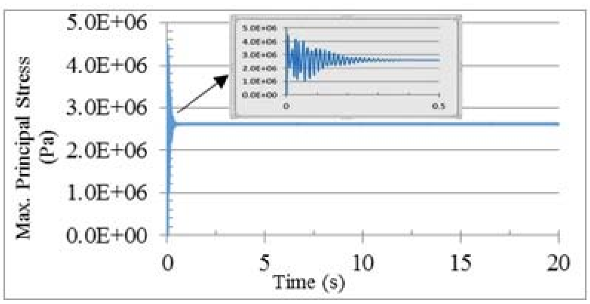

Figure-10a. Maximum principal stress for case-1.

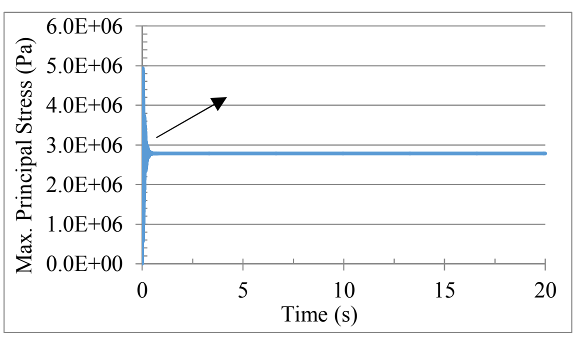

Figure-10b. Maximum principal stress for case-2.

Moreover, when V_{SL} increased from 0.86 m/s to 1 m/s the principal stress σ_{max} was increased by 23.7% as shown in Figure-10c. Generally, the induced stresses in the solid pipe have a proportional relation with the slug frequency and slug transition velocity as well. In contrary, it was observed that there is a reverse relation between the induced stresses and the slug length.

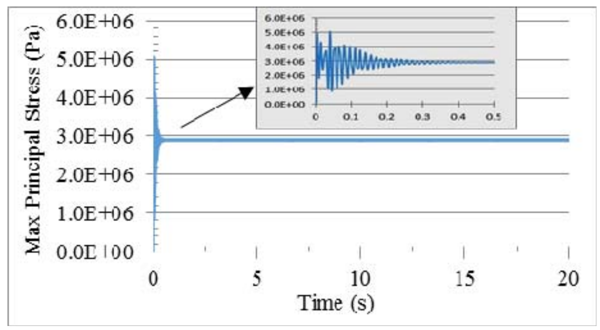

Figure-10c. Maximum principal stress for case-3.

CONCLUSIONS

This study analyzed the internal air-water two-phase slug flow behavior in a horizontal pipe and explained a numerical procedure that assesses the fluid structure interaction between the pipe and the slug flow. The file-based coupling technique, which couples the CFD solver (Star CCM+) and the FEA solver (Abaqus) was utilized to simulate the effects of the pressure fluctuations due to slug flow on the structural pipe. The pressure fluctuations results from Star-CCM+ were mapped to the CAE model, then exported to the Abaqus in order to determine the induced stresses. To address the effect of the slug flow on the structural pipe, a benchmark analysis was conducted for single phase water flow inside the pipe and it was observed that the maximum obtained stresses for single phase flow was less by 63% from the maximum stresses of case-2, in which the slug generated from similar water velocity V_{SL}= 0.86m/s. Three cases of air-water phases have been analyzed in order to clearly identify the effect of the slug characteristic on the induced stresses. For the fluid domain, it was found that the slug frequency and velocity increased when the superficial water velocity increased while the slug length decreased with increasing the superficial water velocity. For the structural domain, it was found that the induced stresses have a proportional relation with the slug velocity and frequency; meanwhile, they have a reverse relation with the slug length. The main goal of the future work is to experimentally validate these numerical outcomes and clearly correlate the induced stresses to the slug characteristics.

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