Underwater oil jet breakup: Numerical simulation and comparison with experimental results

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***Abstract*— Leaking oil behavior is complex and poses difficulties during the clean up efforts. The scope of this study is to examine the trajectory of an oil jet through 2D numerical simulations, to identify the break up regimes and to compare the results with experimental data in order to validate the simulation setup used for the examination of the operation of a recovery system.**

Keywords—oil jet; ANSYS Fluent; well blowout; numerical simulation; jet breakup length

I. INTRODUCTION

Uncontrolled subsurface releases of fluids caused by blowouts are often encountered with severe consequences for the environment and the marine wildlife. At the source, the blowout usually releases a mixture of crude oil, gases and water as a jet which is driven by buoyancy and its own momentum towards the sea surface. It is of great importance to understand the behavior and the breakup patterns of such jets in order to develop an effective mechanism able to contain subsurface leaks, such as DIFIS system [1].

During the recent years, various studies dealing with subsurface oil releases have been carried out. North et al. [2] studied the dispersion of oil droplets using a 3D hydrodynamic model in conjunction with a Lagrangian transport model after the Deepwater Horizon accident. Tanning [3] indicated the increased possibility of an accident which could lead for another time to severe damage of the environment and the marine wildlife.

Brandvik et al. [4] conducted experiments to investigate the impact of dispersant injection on oil droplet size. Sim [5] modeled the spatial-temporal dynamics of a deepwater well blowout using the 'Blowout and Spill Occurrence Model' while Moradi and Hosseinitoudeshki [6] investigated hidden faults in oilfield of Alborz in Iran.

Panopoulos and Margaris [7] examined the application and the efficiency of a cavity separator in a vertical tube with air-water flow. Giannoulis and Margaris [8] studied the behavior of leaking oil and gas under seawater current conditions in order to examine DIFIS system's positioning and conducted simulations for examining various scenarios of the two and three phase flows formed during the operation of the system [9-12].

In this paper the objective is to identify the flow regimes wherein oil jet breakup occurs and to compare experimental results from the study of Masutani and Adams [13] with the results from the numerical simulations of the above experiments using ANSYS Fluent 15 [14].

II. COMPUTATIONAL DETAILS

The geometry and the mesh have been developed in Gambit 2.2.30 [15] as shown in Fig. 1. The 2D mesh contains 320000 quadrangle cells of 0.5 mm width which corresponds to 1/10th of the inlet dimension (orifice) which is 5 mm. The atmospheric pressure tank where the experiments were conducted measures 0.55 m x 0.55 m x 1.3 m. However, the mesh used would require too much computational effort for the geometry with the above dimensions, so it was preferred to model a smaller part of the geometry, 0.2 m x 0.4 m, with pressure outlet boundary conditions instead of wall. Taking into account that the break up patterns and length depend on the inlet velocity, the orifice diameter and the liquid properties, it is expected that the results will not be affected by this choice.

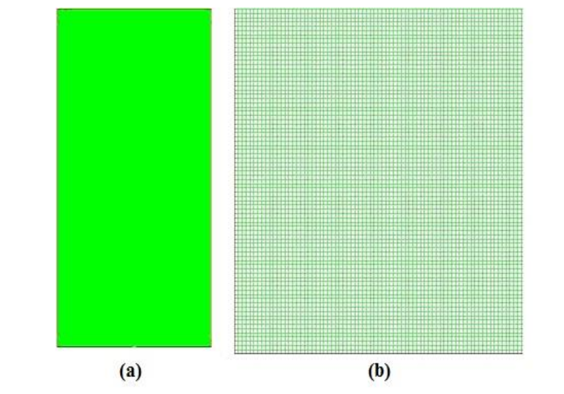

Fig. 1. *(a) Computational domain, (b) Closer view*

Considering that in the simulations the computed interfaces among water and oil should be clear, as these fluids are almost immiscible, the VOF model is used. It can model numerous immiscible phases by solving a separate set of transport equations and tracking the interfaces throughout the computational domain.

Laminar model is used because the small inlet diameter and oil jet velocities yield to maximum Reynolds number of 169.

A. *Materials*

The primary phase in all cases is water while the secondary phase is oil with properties presented in Table I.

TABLE I. OIL PROPERTIES

Oil Name	ρ (kg/m^3)	μ (Pa.s)	σ (N/m)
Genesis (G5T)	877	0.018	0.0259
Mars TLP (M5T)	882	0.024	0.0259
Platform Gail (P5T)	922	0.196	0.0259

ρ, μ, and σ are fluid density, dynamic viscosity and interfacial tension respectively. It should be mentioned that, according to the authors, the interfacial tension was not measured but estimated from data for similar oils.

B. *Solution Controls*

Pressure-Velocity coupling is obtained by using the SIMPLE algorithm. Due to the buoyancy driven flow and since the gravity is predominant, PRESTO interpolation scheme is used for pressure. Geo-Reconstruct scheme for volume fraction discretization fits the simulations as it calculates accurately the interface among the phases. A value of 10^{-6} is used for all residual terms.

C. *Equations*

The dimensionless parameters used to characterize the instability of the jet are the following:

$$Re_D = \frac{U_o D}{v_o} \quad (1)$$

$$We = \frac{\rho_o U_o^2 D}{\sigma} \quad (2)$$

$$Oh = \frac{\mu_o}{\sqrt{\rho_o \sigma D}} = \frac{\sqrt{We}}{Re_D} \quad (3)$$

ρ_o, v_o, μ_o, and σ are jet fluid density, kinematic viscosity, dynamic viscosity and interfacial tension, D is the orifice diameter and U_o the jet inlet velocity.

The Reynolds number (1) of the jet at the outlet is the ratio of momentum to viscous forces, the Weber number (2) is used to express the ratio of hydrodynamic forces to surface tension forces and the Ohnesorge number (3) represents the ratio of viscous forces to inertia and surface tension forces.

The examined cases, the fluid temperatures and the Reynolds and Weber numbers are presented in Table II.

TABLE II. EXAMINED CASES

Case	Water Temperature [C]	Oil Temperature [C]	Jet Velocity [m/s]	Re	We
G5T	19.2	26.9	0.085	22.6	1.22
G5T	19.2	26.9	0.161	42.8	4.39
G5T	19.2	26.9	0.252	67	10.7
G5T	19.2	26.9	0.357	94.7	21.5
G5T	19.2	26.9	0.441	117	32.9
G5T	19.2	26.9	0.637	169	68.5
M5T	17.2	28.1	0.064	13.2	0.69
M5T	17.2	28.1	0.093	19.4	1.48
M5T	17.2	28.1	0.145	30.1	3.58
M5T	17.2	28.1	0.169	35	4.85
M5T	17.2	28.1	0.235	48.8	9.39
P5T	17.9	27.8	0.115	3.87	2.37
P5T	17.9	27.8	0.126	4.24	2.84
P5T	17.9	27.8	0.194	6.49	6.66
P5T	17.9	27.8	0.286	9.59	14.5
P5T	17.9	27.8	0.398	13.3	28.2
P5T	17.9	27.8	0.619	20.8	68
P5T	17.9	27.8	0.34	11.4	20.5
P5T	17.9	27.8	0.679	22.8	81.9
P5T	17.9	27.8	0.441	14.8	34.6

III. RESULTS AND DISCUSSION

When a liquid jet issues into another immiscible fluid, it becomes unstable and breakup occurs a few meters above the release point. Jet instability is promoted by interfacial tension, gravitational effects, viscous forces and velocity difference at the interface.

The progress in the break up pattern with increasing velocity is presented in Fig. 2 as a plot in dimensionless Re-Oh space. At lower velocities, where Rayleigh instabilities are dominant, jet break up occurs near the source, resulting in droplets with larger diameter than the orifice. Type I instability, according to Masutani and Adams [13], occurs at slightly higher velocities with the break up location moving upwards and resulting in narrow polydispersion of large droplets. Type II instability appears at higher velocities as two separate mechanisms operating simultaneously:

- jet core breaks up into large droplets further downstream
- jet surface becomes unstable and disintegrates into droplets near the orifice

As shown in Fig. 2, for Genesis oil, Rayleigh instabilities are dominant up to 0.252 m/s, for Mars oil up to 0.235 m/s and for Platform Gail up to 0.441 m/s.

Type I and II modes occur only for Genesis oil and Platform Gail above 0.357 m/s and 0.619 m/s respectively.

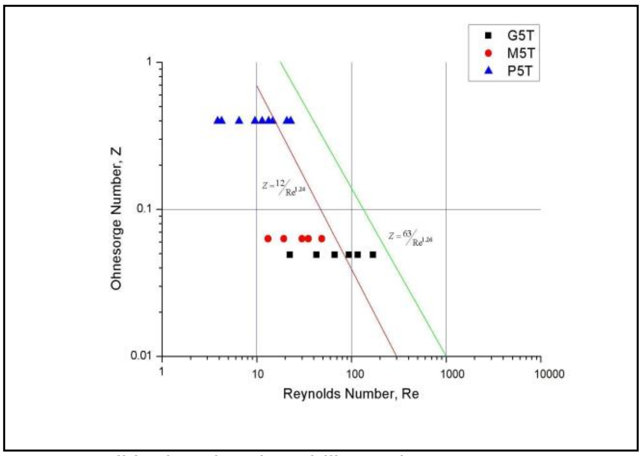

Fig. 2. *Oil jet breakup instability regimes*

In Fig. 3, 4 and 5 are presented the results from the numerical simulations along with the experimental ones concerning the break up length for all cases examined. It is obvious that there is a very good agreement between the simulation results and the experimental data for most of the examined oil jet velocities, taking into account the uncertainty about the interfacial tension and the fact that the simulations conducted in 2D grid. More specifically, there is an average divergence of 14.8% for Genesis oil, 7.1% for Mars oil and 4.3% for Platform Gail.

Another significant behaviour of the flow observed is the uncertainty in the break up length which occurs over a range of distances from the source in the experiments of Masutani and Adams [13] as well as in the numerical simulations. As reported by the authors, the break up length varied in some cases by 80%. In Fig. 6, 7, and 8 are presented these fluctuations in the break up length for three representative cases from the three different oil types examined. It is obvious that the maximum divergence from the mean value for Genesis oil is 19%, for Mars oil 75% and for Platform Gail 29%.

In Fig. 9 through 11 are presented the contours of oil phase for all examined cases where are obvious the different break up patterns observed.

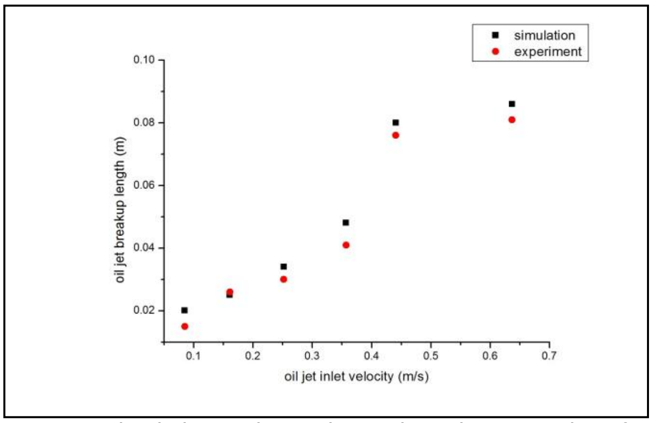

Fig. 3. *Simulation and experimental results comparison for Genesis oil jet breakup*

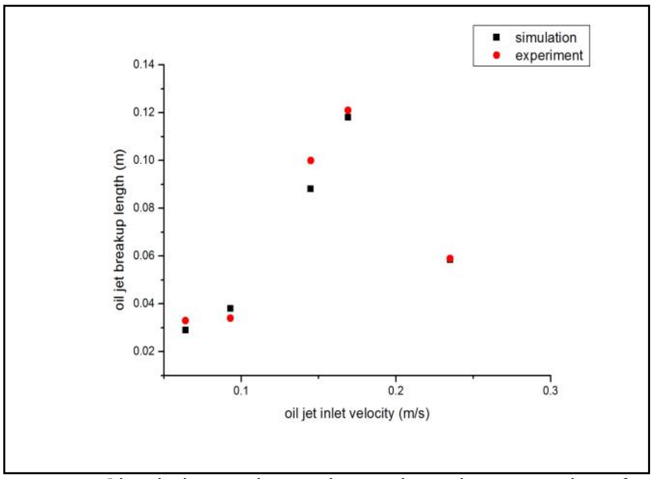

Fig. 4. *Simulation and experimental results comparison for Mars oil jet breakup*

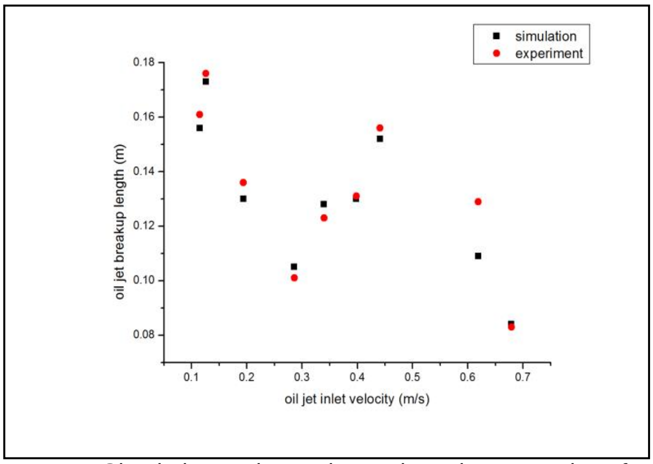

Fig. 5. *Simulation and experimental results comparison for Platform Gail oil jet breakup*

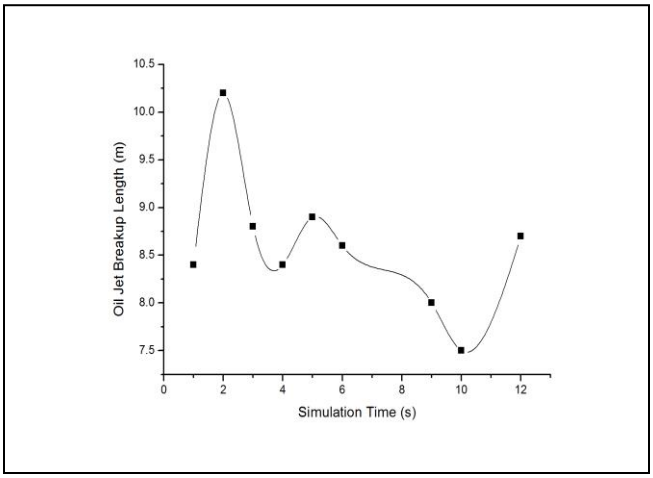

Fig. 6. *Oil jet breakup length variation for 0.637 m/s, Genesis oil*

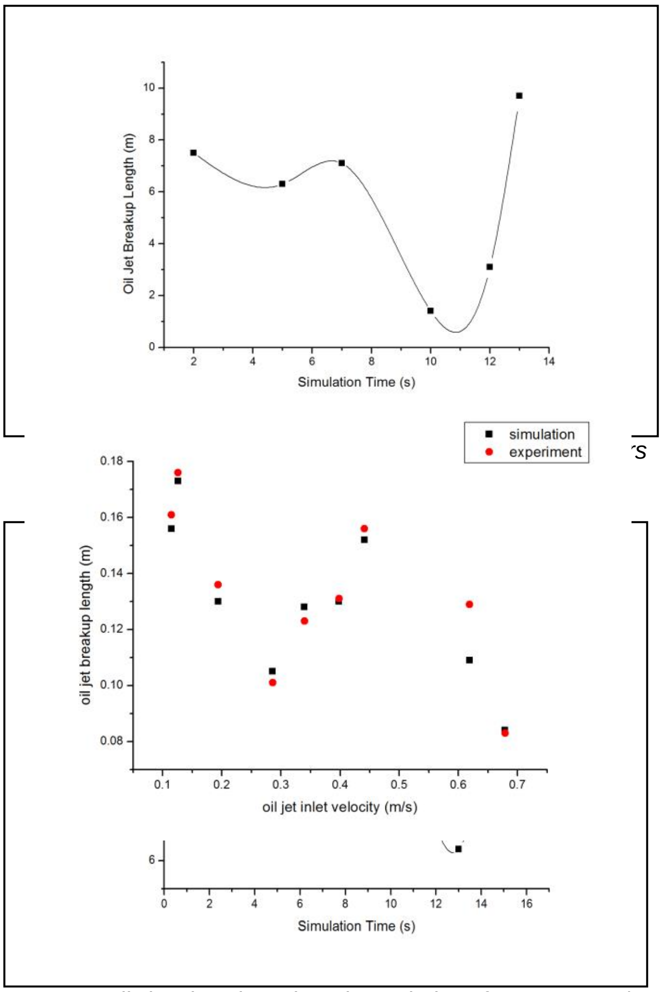

Fig. 8. *Oil jet breakup length variation for 0.679 m/s, Platform Gail oil*

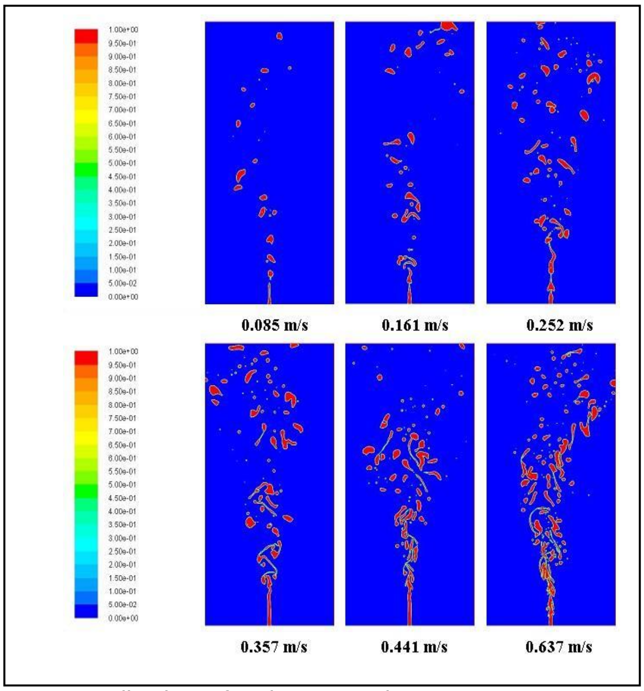

Fig. 9. *Oil volume fraction, Genesis*

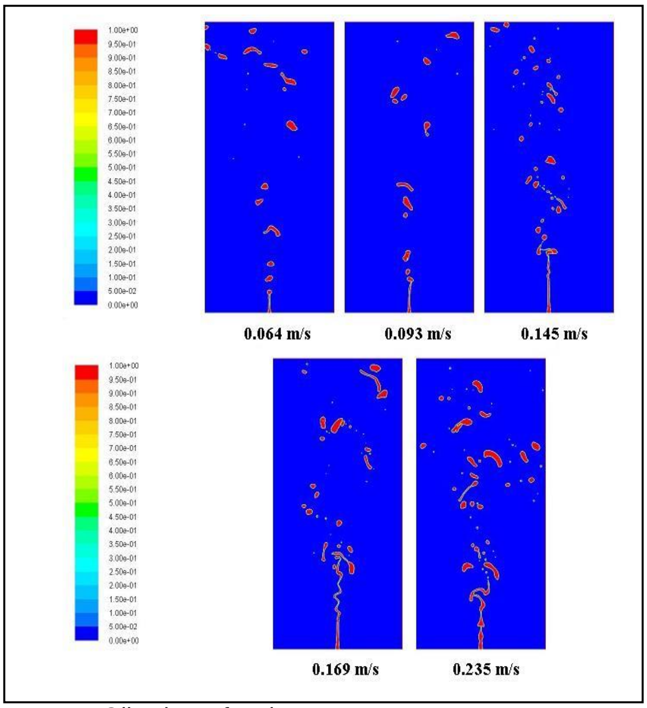

Fig. 10. *Oil volume fraction, Mars*

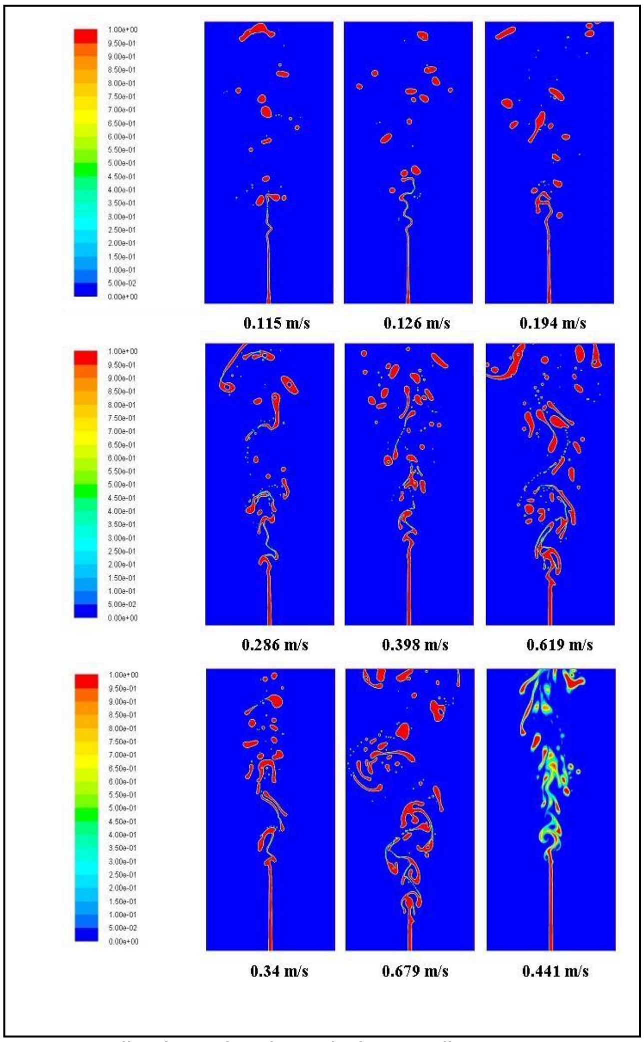

Fig. 11. *Oil volume fraction, Platform Gail*

IV. Conclusion

Underwater oil jets are often encountered either due to natural procedures or due to engineering failures. The present study aims at the identification of the flow regimes where the jet breakup occurs as well as at the comparison of the breakup length with experimental results. Rayleigh, Type I and Type II instabilities where detected, leading to jet breakup while the mean divergence of the break up length compared to the experimental results was 8.73%. Taking into account that the numerical simulations were 2D and that the interfacial tension was estimated and not measured, it is concluded that the results are satisfying and the CFD set up used is appropriate.

References

[1] F. Andritsos, H. Coszijn, “An innovative method for containing offshore oil well blow-outs,” Proc. ASME 30th International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2011-49110, pp. 1-10, 2011.

[2] E. W. North et al., “Simulating Oil Droplet Dispersal from the Deepwater Horizon Spill with a Lagrangian Approach,” Geophysical Monograph Series, vol. 195, pp. 217-226, January 2011.

[3] L. Tanning, T. Tanning, “Analysis of the fossil fuels situation of new members of the European Union to 2014,” Journal of Multidisciplinary Engineering Science and Technology, vol. 2, Issue 1, pp. 345-355, January 2015.

[4] P. J. Brandvik, O. Johansen, U. Farooq, G. Angel, F. Leirvik, “Subsurface oil releases-Experimental Study of Droplet Distributions and Different Dispersant Injection Techniques-version2,” SINTEF Materials and Chemistry Report, May 2014.

[5] L. H. Sim, “Blowout and Spill Occurrence Model,” Master of Science, Oregon State University, June 2014.

[6] H. R. Moradi, V. Hosseinitoudeshki, “Discovering Hidden Faults Under the Oil Field of Alborz Anticline in Qom, Iran,” Journal of Multidisciplinary Engineering Science and Technology, vol. 3, Issue 2, pp. 4080-4085, February 2016.

[7] N. Panopoulos, D. P. Margaris, “CFD investigation of air-water separation using a cavity separator in vertical slug and churn flow,” Journal of Multidisciplinary Engineering Science and Technology, vol. 4, Issue 1, pp. 6482-6487, January 2017.

[8] D. P. A. Giannoulis, D. P. Margaris, “A first approach on positioning DIFIS system for containing oil and oil-gas leaks,” Journal of Multidisciplinary Engineering Science and Technology, vol. 2, Issue 10, pp. 2872-2876, October 2015.

[9] D. P. A. Giannoulis, D. P. Margaris, “Computational study of the two-phase flow formed within the vertical pipe of a system designed to remove leaking oil from maritime accidents,” International Review of Mechanical Engineering, Vol. 6 N. 7, pp. 1694-1699, 2012.

[10] D. P. A. Giannoulis, D. P. Margaris, “Numerical simulation of the three-phase flow formed within the riser tube of a system designed to remove leaking oil from maritime accidents”, International Review of Mechanical Engineering, Vol. 8 N. 1, pp. 94-99, 2014.

[11] D. P. A. Giannoulis, D. P. Margaris, “Assessment of the behavior, of oil trapped in the riser tube of an oil spill prevention system based on buoyancy driven flow”, International Review of Mechanical Engineering, Vol. 8 N. 6, pp. 1110-1115, November 2014.

[12] D. P. A. Giannoulis, D. P. Margaris, “Numerical simulation of the three phase flow formed during the containment of an oil-methane leak using the DIFIS system”, International Review of Mechanical Engineering, Vol. 9 N. 6, pp. 576-582, November 2015.

[13] S. M. Masutani, E. E. Adams, “Experimental study of multi-phase plumes with application to deep ocean spills,” Final Report, University of Hawaii, October 2012.

[14] Fluent Inc., Fluent 15 Documentation-User’s Guide, 2013.

[15] CFD Pre-processor, Gambit 2.3 Documentation, 2004.