CFD Modeling of Dust Explosions: DESC Applications for Industrial Scenarios

Meftah Abuswer
Department of Chemical Engineering, College of Technical Science/Misurata, Libya

mabuswer@CTSM.edu.ly & mabuswer@dal.ca

Abstract – CFD (computational fluid dynamics) codes can be used to good advantage for investigating industrial explosion phenomena, especially in complex geometries. This is a relatively new approach to assess the consequences of industrial explosions; the Dust Explosion Simulation Code (DESC) developed by GexCon (Norway) is one of few comprehensive packages available at this time.

DESC has been validated by the current author as the first step in their numerical research program on dust and hybrid mixture explosions. The maximum explosion pressures produced by DESC simulations in 20-L and 1-m^3 spherical vessels were compared with relevant experimental data for -200 mesh polyethylene dust; error percentages were found to be less that 5 %. The DESC software was also used to simulate two recent accidents: the Imperial sugar refinery explosion in Georgia, US, in 2008, and the grain storage facility explosion in Blaye, France, in 1997. Additionally, simulations were performed for a 400-m3 silo to predict the consequences of polyethylene and polyethylene/hydrocarbon explosions.

The maximum pressure of an explosion is the most important parameter to consider when determining its consequences. Thus, pressure-time curves at different points in each given geometry were plotted in the DESC post-processor (Flowvis). Subsequently, the simulation results and the actual data were compared and analyzed. The comparisons were favourable, meaning that DESC can be helpful in optimizing mitigation measures for dust explosion risk reduction.

I. INTRODUCTION

Important to those interested in the industrial safety area is the history of industrial accidents such as explosions, fires, and toxic releases. Chemical industries have the majority of these accidents, especially dust and hybrid mixture explosions. A hybrid mixture is a combination of a flammable gas and a combustible dust, where gas may be present in an amount less than its lower flammable limit (LFL) and also an amount of dust less than its minimum explosible concentration (MEC). Nevertheless, they may, in combination, create an explosible mixture [1]. Eckhoff (2003) demonstrated that the addition of flammable gas to a dust cloud significantly increases the explosion violence [2]. Likewise, Amyotte et al. (2010) showed experimentally the increased maximum explosion pressure (P_{max}) and maximum rate of pressure rise in constant-volume (K_{St}) for ethylene/polyethylene, hexane/polyethylene, and propane/polyethylene mixtures. The methane/coal dust system is the most dangerous and volatile hybrid mixture in underground coal mines [3].

Because many industries handle fine powders (dust) and hybrid mixture during their processing stages, combustible dust and hybrid mixture explosions have become serious hazards that can threaten processing plants harm people, and damage the environment, production, and/or processing equipment.

Consequently, research and efforts have been continuing to prevent or mitigate these explosions. However, it is still difficult to predict the severity of consequences of any expected explosion in large scales.

Frank (2004) and Amyotte & Eckhoff (2010) show that dust explosions occur in a wide range of industries and industrial applications involving numerous and varied products such as coal, grain, paper, foodstuffs, metals, rubber, pharmaceuticals, plastics, textiles, etc. Industries that handle combustible dust or hybrid mixtures during at least one of their processing stages are at risk of explosions that can threaten processing plants and harm people as well as damage the environment, production, and/or processing equipment [4] [1].

Therefore, there is an urgent need in the process industry to develop a tool that combines various safety methodologies, software, procedures, etc., to prevent dust and hybrid mixture explosions. Unfortunately, few published papers in the explosion area deal with dust/hybrid mixture explosion risk assessment, mainly due to the complex nature of these phenomena [5].

In the late 1990s, Khan and Abbasi (1998) developed the software package MAXCRED (Maximum Credible Accident Analysis) to conduct rapid quantitative risk studies and comprehensive risk analyses of the petrochemical industry [6]. A few years later, Khan & Abbasi (2001) developed another computer program called TORAP (Tool for Rapid Risk Assessment in Petroleum Refinery and Petrochemical Industries), which is used for conducting rapid risk assessment in the chemical process industry (CPI) and is capable of handling many types of industrial fires and explosions [7]. Pula et al. (2005) revised several fire consequence models for offshore Quantitative Risk Assessment [8]. Abuswer et al. (2011) developed a quantitative risk management framework (QRMF) for dust and hybrid mixture explosions. The framework was applied to some industrial case studies, using CFD modeling software, and shows great results that reduced the explosion risk to the acceptable region [9], as indicated in the ALARP measure tool, as shown in Abuswer et al. (2013) [10].

CFD (computational fluid dynamics) modeling are becoming increasingly important, particularly for materials and large-scale scenarios that are difficult or impossible to study experimentally. CFD codes can be used to good advantage for investigate dust explosion phenomena, especially in complex geometries. The Dust Explosion Simulation Code FLACS-DustEx (former DESC) developed by GexCon (Norway) is one of the most comprehensive package available at this time. It is a CFD code for simulating the course of industrial dust explosions in complex geometries.

As described by Skjold (2007), DESC can be helpful as a plant design tool for the optimization of mitigation measures such as explosion barriers, vents, and suppression systems, also Applying DESC beside other safety methodologies, such as inherent safety, decrease the high-risk of industrial processes [11]. It can be used also to provide simulation assistance throughout industries that handle explosible dust samples [12].

DESC has been validated by the current author as the first step in his numerical research program on dust and hybrid mixture explosions. The maximum explosion pressures produced by DESC simulations in 20-L and 1-m^3 spherical vessels were compared with relevant experimental data for icing and granulated sugar, and -200 mesh polyethylene; error percentages were found to be less that 5 %.

Preparation of fuel file, which is the primary step to begin working on DESC simulations. The fuel file is produced by an Excel spreadsheet (as shown in Figure 1), which is prepared by the GexCon technical team. It should be filled-in with experimental data that have been taken from an explosion laboratory using a 20-L Siwek chamber for the fuel used. The required data are K_{St} , P_{max} ,$(dp/dt)_{max}$, particle density, particle size, and some of dust thermodynamic properties. The new fuel file should be inserted in the working directory to be read by DESC simulation Run Manager.

Using DESC to simulate a certain dust explosion should follow go through the following steps:

1- Build and name the explosion geometry at the DESC pre-processor CASD (Computer Aided Scenario Design), or it can import the geometry from AutoCAD program.

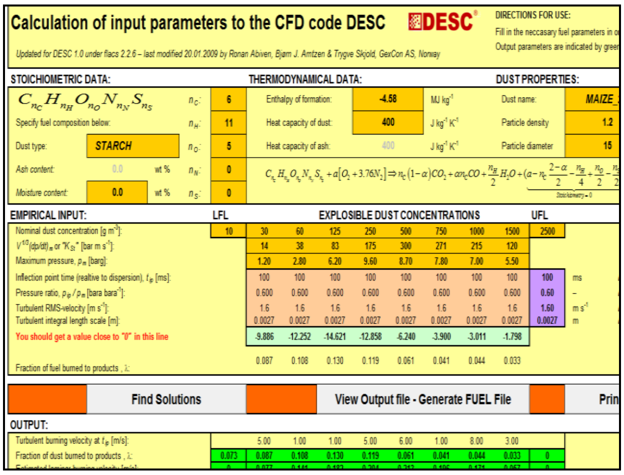

Figure 1. Part of DESC excel spreadsheet.

2- Fill the DESC required parameters such as; geometry monitor points, initial and boundary condition, fuel information (name, composition, position and shape), and ignition source (position and strength in KJ).

3- Run the job at the “Run manager” program, it could take from few minutes to some hours. The DESC calculations and plotting curves can be monitored while the program is running.

Simulation development of the explosion temperature, pressure, and fuel consummation can be displayed in 2-D and 3-D at Flowvis program.

II. DESC VALIDATION

Skjold (2007) discussed DESC validation work that was performed by GexCon Company research team in the years of (2005 & 2006), and the reasonable results they have got from DESC simulations compared with experimental data obtained in relatively simple geometries like silos.

In the present work, the DESC program has been validated by comparing the maximum output pressure produced by DESC simulations in 20-L and 1-m^3 spherical vessels with relevant experimental data for Granulated and Icing sugar dust. Figures 2 – 5 show simulation results thus obtained for explosions of the sugar samples (all with central ignition and a dust concentration of 500 g/m^3).

Figure 2 and 3 are drawn for the Icing sugar in 20-L and 1-m^3 chambers. The highest explosion pressure attained in both of them is 7.2 bar(g), which is within 3 % of the experimental value. As shown in Figure 4 and 5, the peaks overpressure of the Granulated sugar in 20-L and 1-m^3 chambers was the same, 6.9 bar(g). The sugar explosions in the chambers, for each case, have similar P_{max} but with longer time to attainment of P_{max}. Similarly, more time is needed to reach the peak overpressure in Figure 6 - 7 (400-m^3 silo).

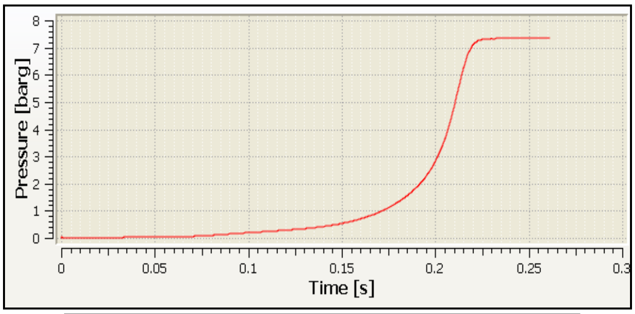

Figure 2 DESC simulation of Icing Sugar explosion in a 20-L spherical chamber.

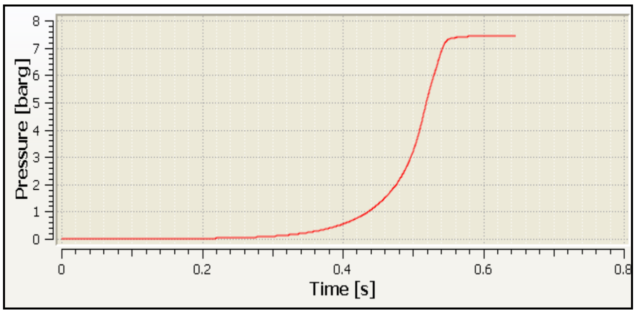

Figure 3 DESC simulation of Icing Sugar explosion in a 1-m^3 spherical chamber.

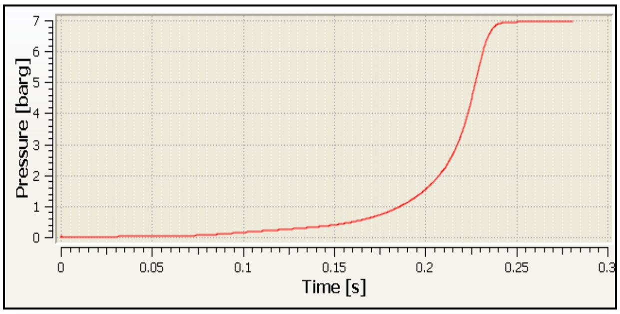

Figure 4 DESC simulation of Granulated Sugar explosion in a 20-L spherical chamber.

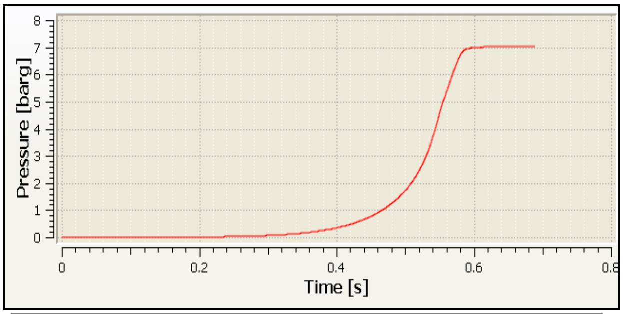

Figure 5 DESC simulation of Granulated Sugar explosion in a 1-m^3 spherical chamber.

III. DESC SIMULATIONS:

A. Imperial Sugar Refinery dust explosion:

The Imperial Sugar Refinery (Georgia, US) was consisting of three granulated sugar storage silos (32 m

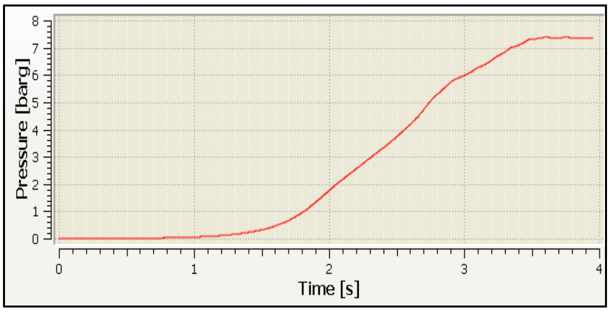

Figure 6 DESC simulation of Icing Sugar explosion in a 400-m3 cylindrical silo without explosion vents.

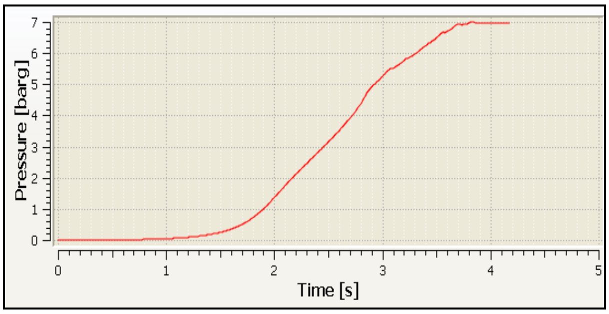

Figure 7 DESC simulation of Granulated Sugar explosion in a 400-m^3 cylindrical silo without explosion vents.

tall and 12.2 m in diameter), as can be seen in Figure 8, which exploded in February 7, 2008 (Abuswer et al., 2013); M1 – M14 represent DESC pressure monitoring points in both the storage silos and the interconnecting galleries, with wall destruction in the galleries simulated by pressure relief panels set to open at 1 bar(g). The US Chemical Safety Board web site (www.csb.gov) gives further details on the actual plant layout as well as incident causation.

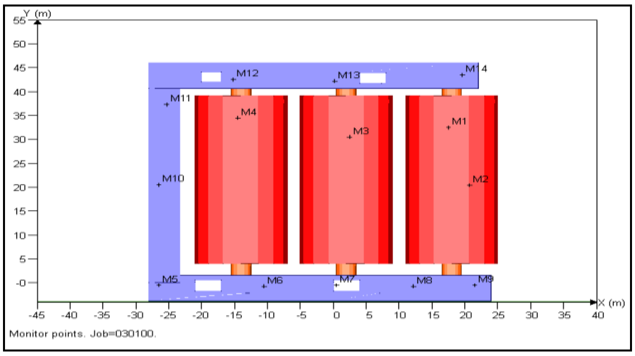

Figure 8 DESC representation of interconnected 3700-m^3 silos.

Figures 9 and 10 show the maximum pressure output, of 40-µm Icing sugar and 79-µm Granulated sugar explosions, produced by DESC at 3700-m^3 Imperial Sugar Silos geometry with explosion vents (PP 2 bar), respectively. The maximum explosion pressure reached of the Icing sugar explosion is 6.4 barg, and 5.9 barg for the granulated sugar explosion. Figure 11 is two 2-D

(XY) and (XZ) cut-plane images, which are show temperature developments of the Imperial Sugar silos geometry at 2.097 s in CASD.

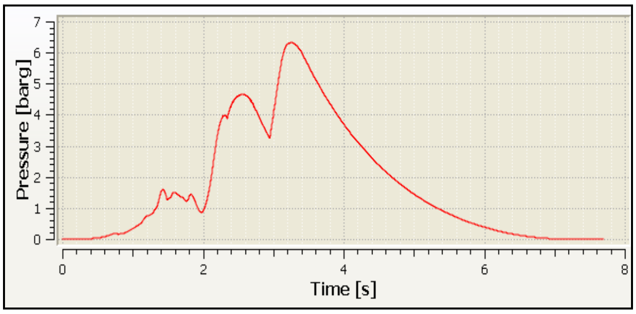

Figure 9 DESC simulation of Icing Sugar explosion in a 3700-m^3 Imperial Sugar Silos geometry with explosion vents (PP 2 bar).

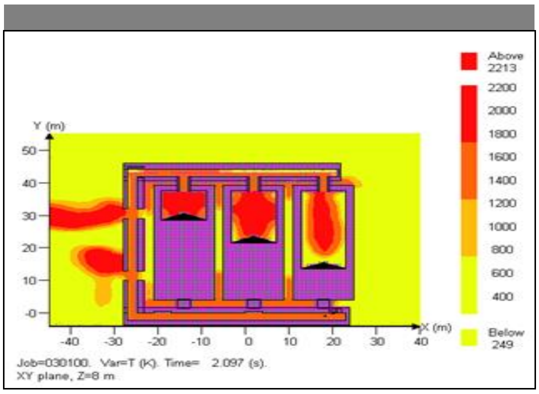

Figure 11. 2D cut-plane images of the Imperial Sugar silo simulation show temperature developments at 2.097 s.

B. *400-m^3 cylindrical silo Polyethylene dust explosion:*

As mentioned our current interest in DESC is for the prediction of explosion consequences for industrial-scale process units. An example is the arrangement of storage silos at a polyethylene production facility Figure 12 and 13. Of concern is the maximum explosion pressure to be expected for various combinations of parameters such as explosible dust concentration, flammable gas percentage, and ignition source location. Our work to date has been on dusts alone and is preliminary, and only tentative conclusions are drawn at present. The results appear promising, however, and indicate the usefulness of the CFD approach for dust and hybrid mixture explosions.

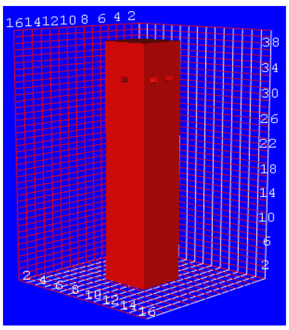

Figure 12. 3D CASD image of polyethylene silo (solid style).

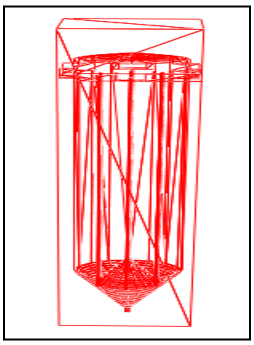

Figure 13. 3D CASD image of polyethylene silo (wireframe style).

The silo simulation takes about 20 minutes to finish. Figure 14 shows that the explosion duration takes 1.8 seconds; however the highest pressure has been recorded was 3.7 barg at 1.15 second.

Also, Figure 15 shows the silo explosion profile at completely closed explosion doors along the explosion duration. The maximum explosion pressure has been reached in the silo was about 7.2 barg. Figure 16, 2D cut-plane (X-Z) image shows the temperature development of Polyethylene dust explosion.

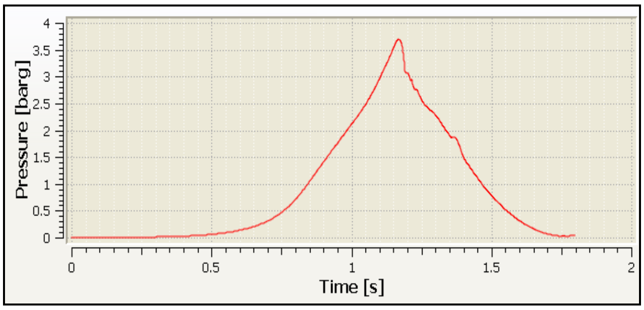

Figure 14. Pressure-time curves of a (-200 mesh) PE silo explosion (the safety explosion doors enabled).

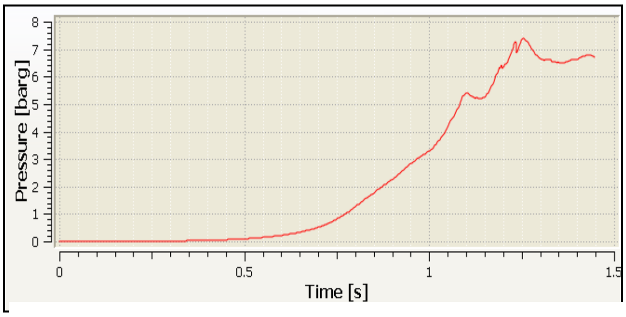

Figure 15, Pressure-time curves of a (-200 mesh) PE silo explosion (The safety explosion doors disabled)

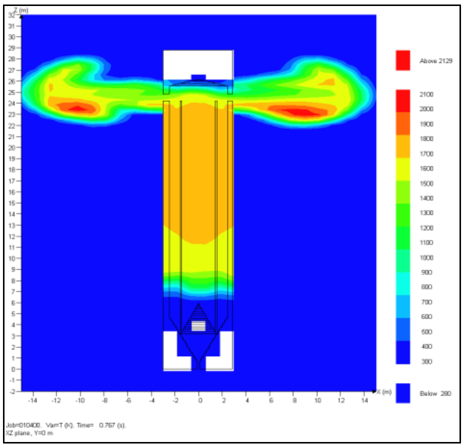

Figure 16. 2D cut-plane (X-Z) image shows temperature development of PE explosion.

IV. DISCUSSION

Figures 9 and 10 show the pressure-time development, where the pressure panels, which acting to simulate the wall damage during the explosion, are adjusted to open when the gage pressure inside the tunnel exceed 2 barg. As can be seen, when the explosion started, the pressure start raises-up then comes down for short time at about 2 (s), because the flame reached the end of the tunnel where it connected with other vertical tunnel, which makes the pressure decrease instantly. The pressure started build-up again till it reached 3.7 bar, where most of the PP are already opened (at 2 bar) and their start affect being reduce the explosion pressure. However, the pressure started increase at time equal about 3.0 s, because the flame reached the vertical cylindrical silos, which do not have PP. Then the pressure took it way through the up-silos' gates to the upper tunnel, which is already its PP open to the atmosphere.

In the 400 m^3 cylindrical silo, Figure 14, where the PP adjusted to open at 3 barg, the maximum pressure reached 3.7 barg at 1.15 (s). Even though the pressure panels opened at 3 barg, the explosion pressure accelerates much faster, it keeps rises to the 3.7, then start decrees by the effect of pressure relief panels.

The comparison, at the same geometry (400-m^3 cylindrical silo) between the Icing sugar and the Polyethylene plots can show the difference between the fuel burning velocities. While the icing sugar explosion took about 4 (s), the Polyethylene explosion time is less that 1.5 (s).

V. CONCLUSION

This paper has demonstrated various dust explosion simulation using DESC. It showed how much the CFD modeling are becoming increasingly important, particularly for materials and large-scale scenarios that are difficult or impossible to study experimentally. What is required for the wide adoption of these techniques is continued validation of the model predictions with experimental data where possible, coupled with calibration against known and expected explosion phenomena.

REFERENCE

[1] Amyotte, P. R., & Eckhoff, R. K. (2010). Dust explosion causation, prevention and mitigation: An overview. Journal of Chemical Health and Safety, 17(1), 15-28.

[2] Ekhoff R., K. (2003). Dust explosions in the process industries (Third Edition ed.) Gulf Professional Publishing.

[3] Amyotte, P., Abuswer, M., Di Benedetto, A., & Russo, P. (2010). Determination of hybrid mixture explosion severity. 13th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Brugge, Belgium. , 02, 149-156.

[4] Frank, W. L. (2004). Dust explosion prevention and the critical importance of housekeeping.23(3), 175-184. doi:doi: 10.1002/prs.10033.

[5] Markowski, A. S. (2007). exLOPA for explosion risks assessment. Journal of Hazardous Materials, 142(3), 669-676.

[6] Khan, F. I., & Abbasi, S. A. (1998). Rapid Quantitative Risk Assessment of a petrochemical industry using a new software package MAXCRED. Journal of Cleaner Production, 6(1), 9-22.

[7] Khan, F. I., & Abbasi, S. A. (2000). TORAP — a new tool for conducting rapid riskassessments in petroleum refineries and petrochemical industries. Applied Energy, 65(1-4), 187-210.

[8] Pula, R., Khan, F. I., Veitch, B., & Amyotte, P. R. (2005). Revised fire consequence models for offshore Quantitative Risk Assessment. Journal of Loss Prevention in the Process Industries, 18(4-6), 443-454.

[9] Abuswer, M., Amyotte, P. R., & Khan, F. (2011). A quantitative risk management framework for dust and hybrid mixture explosions, Journal of Loss Prevention in the Process Industries (2011), doi:10.1016/j.jlp.2011.08.010.

[10] Abuswer, M., Amyotte, P. R., Khan, F, & Morrison, L. "An optimal level of dust explosion risk management: Framework and application", Journal of Loss Prevention in the Process Industries, Volume 26, Issue 6, November 2013, Pages 1530 – 1541. doi: http://dx.doi.org/10.1016/j.jlp.2013.08.018

[11] Skjold, T., Review of the DESC Project, Journal of Loss Prevention in the Process Industries, 20, 291-302 (2007).

[12] Ghaffari, M., Skjold, T., van Wingerden, K., Hisken, H., Eckhoff, R.K. & Hoffmann, A.C. (2016). A model validation framework for the explosion simulator FLACS-DustEx: challenges, limitations and possibilities. Proceedings Eleventh International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions, Dalian, 24-29 July 2016: 223-238. ISBN 978-7-89437-165-2.

ACKNOWLEDGMENT

The author wish to thank Dr. Paul Amyotte, the Chemical Engineering professor at Dalhousie University/ Canada, for his great help and support.

BIOGRAPHIES

Meftah Ali Abuswer was born in Misurata /Libya, on September 19, 1967. He received B.Sc. degree in Chemical Engineering from University of Tripoli/ Libya, in 1991. He got M.Sc. degree in Chemical Engineering from University of Tripoli/ Libya, in 2003. Moreover, he got his Ph.D. degree in Chemical Engineering from Dalhousie University/ Canada in 2012, where he is currently the Dean & lecturer at the College of Technical Science/Misurata. His research field is Industrial safety & Loss prevention.