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Chapter

BLEVE Fireball Effects in a Gas Industry: A Numerical Modeling Applied to the Case of an Algeria Gas Industry

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Abstract

This chapter presents the numerical modeling of the BLEVE (Boiling Liquid Expanding Vapor Explosion) thermal effects. The goal is to highlight the possibility to use numerical data in order to estimate the potential damage that would be caused by the BLEVE, based on quantitative risk analysis (QRA). The numerical modeling is carried out using the computational fluid dynamics (CFD) code Fire Dynamics Simulator (FDS) version 6. The BLEVE is defined as a fireball, and in this work, its source is modeled as a vertical release of hot fuel in a short time. Moreover, the fireball dynamics is based on a single-step combustion using an eddy dissipation concept (EDC) model coupled with the default large eddy simulation (LES) turbulence model. Fireball characteristics (diameter, height, heat flux and lifetime) issued from a large-scale experiment are used to demonstrate the ability of FDS to simulate the various steps of the BLEVE phenomenon from ignition up to total burnout. A comparison between BAM (Bundesanstalt für Materialforschung und –prüfung, Allemagne) experiment data and predictions highlights the ability of FDS to model BLEVE effects. From this, a numerical study of the thermal effects of BLEVE in the largest gas field in Algeria was carried out.

Keywords: BLEVE effects, CFD, FDS, fireball, LES, QRA

1. Introduction

After the industrial revolution of the nineteenth century, the world has experienced significant growth in new technologies embedded in the process industry such as gas processing, manufacture of transportation means, etc. In these installations, several fuel elements are present and require special attention in order to avoid accidents whose consequences have severe impacts on people, equipment, and environment. The most common accidents encountered in the chemical and petrochemical process industry are fires, explosions, and toxic releases. Considering the number of existing and future installations, the consequences of

these types of accidents remain a major concern for decision-makers, industrial experts, and fire safety analysts.

In the context of defining an accurate assessment of the safety of industrial facilities, risk analysts often use quantitative risk analysis (QRA) [1]. It is an analysis method that makes it possible to understand and quantify the consequences of accidental phenomena (thermal radiation, overpressure, toxicity dose).

Among the accidental phenomena most observed in the process industry is the boiling liquid expanding vapor explosion (BLEVE). It corresponds to a violent vaporization of explosive nature following the rupture (loss of confinement) of a tank containing a liquid at a temperature significantly higher than its normal boiling point at atmospheric pressure [2]. Between 1940 and 2005, the different BLEVEs listed have cost more than 1000 lives and have injured more than 10,000 people in addition to harming property worth billions of dollars [3]. In addition to human lives and material goods, BLEVE has hazardous effects on the environment; it can release dangerous substances likely to attack the environment. Considering this, it is important to estimate the potential damage that would be caused by such an explosion. In this context, several studies have been conducted to analyze the BLEVE mechanisms. Thermal radiation hazards associated with liquefied petroleum gas (LPG) releases from pressurized storage were studied by Roberts [4]. He established correlations allowing to obtain the fireball characteristic parameters from the fuel mass (diameter, lifetime, and heat flux). From these mathematical laws, Crocker and Napier [5] evaluated fire and explosion hazards of LPG. They showed that these models overestimate the risks associated with jet fires, fireballs, and BLEVE blast effects. Prugh [6], in his part, studied the effects of fuel type and fuel quantity on fireball diameter, duration, and energy and the relationships between fireball energy, distance from the fireball, and consequences of personnel and property exposure.

Roberts et al. [7] presented results from a series of experimental tests performed by the Health and Safety Laboratory in the context of JIVE project (hazards consequences of jet fire interaction with vessels containing pressurized liquids). During these tests, several propane tanks were exposed to fires. They allowed to identify the conditions of temperature and rupture pressure, failure mode, as well as the fireball characteristics. In a study conducted by Abbasi et al. [3], the mechanism, the causes, the consequences, the hand calculation methods, and the preventive strategies associated with BLEVEs were presented in an excellent review. Based on medium-scale experimental tests, Birk et al. [8] concluded that the liquid part does not contribute to the generation of shock waves. They proposed a model based on the TNO model that uses the vapor part to calculate the expansion energy. Other works like Bubbico and Marchini [9] and Chen et al. [10] give information on the fact that BLEVE evolution process is characterized by two-phase flow with an overpressure effect.

In works cited above, there are empirical and semiempirical approaches which provide data highlighting the characteristics of BLEVE. However, these approaches are not very satisfactory because they usually include an experimentally adjusted reduction factor and mostly overestimate the BLEVE effects [11–13]. Furthermore, they do not consider the effect of buildings, obstructions, and topography for specific facilities. In addition, the data provided by these approaches may not ensure enough repertory for conducting an in-depth QRA.

In order to overcome the empirical approach limitations, it is necessary to use the computational fluid dynamics (CFD) modeling which appears as a powerful complementary tool for experimental and theoretical studies. Considering the complexity of the BLEVE phenomenon process, current published CFD simulation studies [14–19] focus only on certain BLEVE aspects, such as fireball formation,

without considering vessel disintegration. Indeed, with a sufficiently fine numerical resolution, it is possible to carry out simulations of explosion phenomena considering turbulence, combustion process, heat transfer, and geometry.

Among the numerical studies on the BLEVE, Yakush and Makhviladze [14] compared the fireball lifetime predictions from two turbulence models (based on RANS and LES approach) and the fireball lifetime obtained by the experimental correlation of Roper et al. [15]. The simulations were performed by the CFD code FDS from NIST version 4. They showed that the simulation using LES model better predicts fireball dynamics than the simulation using RANS model. Other simulations were made using the CFD code FDS [16–18]. The FDS validation was carried out using the experimental data such as the BAM BLEVE experiment [19]. They evaluated the code capabilities to simulate the fireball characteristics (diameter, lifetime, flame dynamics, and structure). In addition to FDS, other CFD codes are used to simulate fireball characteristics such as OpenFOAM, Ansys CFX, etc. Indeed, Mishra et al. [20] performed a CFD investigation on a peroxy-fuel BLEVE using the CFD commercial code Ansys CFX, and Shelke et al. [21] used the OpenFOAM CFD code. They highlighted the abilities of these CFD codes to predict the reactive flows present in a fireball such as BLEVE.

In this chapter, in addition to evaluating the capability of the CFD code FDS to predict the BLEVE characteristics, an evaluation of the BLEVE thermal effects on a real gas processing plant is presented. The evaluation of the CFD code is made using data obtained from empirical correlations and large-scale experimental data issued from the literature. The calculations are carried out using the FDS code version 6.

In this context, an overview of the BLEVE phenomenon is presented in the second part of the chapter. In the third part, the capability of FDS to predict BLEVE characteristics is presented in comparison with experimental data. In the fourth part, the BLEVE thermal effects on a real case study are illustrated to finish with conclusions and perspectives in the last part.

2. BLEVE presentation

2.1 BLEVE definition

BLEVE is described as a violent explosive vaporization resulting from the rupture of a tank containing a liquid at a temperature significantly above its boiling point at atmospheric pressure.

BLEVE can occur with any liquid, flammable or not, when heated and pressurized into a closed container. Two types of BLEVE can be distinguished, cold BLEVE and hot BLEVE, depending on the temperature at which the rupture of the enclosure occurs.

In this illustration, the hot BLEVE with a flammable liquid is studied. The BLEVE explosion of hydrocarbon fuels (e.g., LPG, LNG, etc.) is characterized by the formation of fireball and the release of intense thermal radiation in a short time.

2.2 Description of the different BLEVE tests

In the focus to characterize the BLEVE phenomenon with enough accuracy, it is important to define an experimental setup with a fine and controlled

instrumentation. However, the current measurement instruments do not allow the proper acquisition of results during a BLEVE test due to its magnitude. In addition, the high cost of this type of test and considering respect for the environment, there are few experimental tests that deal with this kind of phenomenon. In the literature [19, 22], there are large-scale experiment tests: the BAM test (Bundesanstalt für Materialforschung und –prüfung, Allemagne), the British Gas experiments, and the JIVE tests (hazards consequences of jet fire interaction with vessels containing pressurized liquids, 1994/1995).

In this chapter, only the BAM experiment is used to evaluate the capability of FDS to predict BLEVE characteristics.

By doing a little reminder on the BLEVE phenomenon, in 1998, the BAM conducted a BLEVE test with a road tank of 45 m3 of capacity, containing 5 tons of commercial propane (fill liquid level 22%) [19, 22]. The wagon was exposed to a fuel pool fire. In this test, an instrumentation has been performed to obtain physical quantities such as heat flux, temperature, and pressure.

In the goal to make a comparison between empirical law and numerical modeling, the next sections will present the equations used for the empirical laws and the different models proposed to simulate the reactive flows inducted by the fireball.

2.3 BLEVE modeling using empirical laws

In order to predict the fireball effects, different authors proposed correlations to predict fireball diameter and lifetime based on fuel quantity [4, 23–30]. These correlations are given in the following equations:

$$D_{FB} = a_1 M^{b1} \tag{1}$$

$$t_{FB} = a_2 M^{b_2} \tag{2}$$

where D_{FB} is the fireball diameter, M is the fuel mass, t_{FB} is the fireball lifetime, and a_1, b_1, a_2, and b_2 are empirical constants.

With the difficulty to choose good coefficients which give better correlation for the fireball characterization, a comparative analysis made by Satyanarayana et al. [31] to define the best correlations which describe the fireball diameter and lifetime is given as follows:

$$D_{FB} = 6.14 M^{0.325} \tag{3}$$

$$t_{FB} = 0.41 M^{0.340} \tag{4}$$

Equations (3) and (4) are used in this study in order to compare with the experiment data and CFD predictions.

To estimate the incident radiation received by a target at a given distance, the solid-flame model may be used [23, 27]:
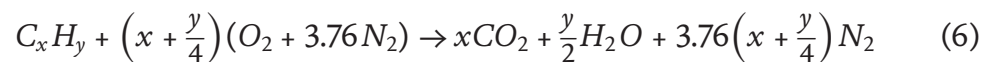
$$\dot{q}_r^n = E_p \cdot F_v \cdot \tau_{atm} \tag{5}$$

where $\dot{q}_r''$ is the radiation received by target, E_p is the surface emissive power, F_v is the view factor, and τ_{atm} is the atmospheric attenuation factor (transmissivity).

3. Numerical modeling of BLEVE

The numerical modelings were performed using the CFD code FDS 6.5.3 [32]. This one solves the Navier–Stokes equations based on an explicit finite difference scheme. Moreover, it models the thermally driven flow with an emphasis on smoke and heat transport. It is a LES model using a uniform mesh and has parallel computing capability using message-passing interface (MPI) [26, 33].

3.1 Fire source modeling

The modeling of the fire is based on a reaction rate considered as infinitely fast, and the combustion is modeled using the EDC of Magnussen and Hjertager [34–36]. The turbulent combustion processes are based on the governing equations for the mass fraction of the chemical species, such as C_xH_y, O_2, CO_2, H_2O, and N_2 through a single step as follows [37]:

$$C_xH_y + \left(x + \frac{y}{4}\right)(O_2 + 3.76\,N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76\left(x + \frac{y}{4}\right)N_2 \quad (6)$$

Considering the complexity of the BLEVE phenomenon, only the fireball is modeled in this work. Indeed, as the published CFD studies say, the container disintegration is complicated to model and is not considered. For that, the present study is based on the BLEVE modeling by fuel release.

The fuel used is propane. Its heat of combustion is set to 46,334 kJ/kg. The ejection surface was calculated using the approach of Makhviladze et al. [38]. The fuel releases as a hot gas with a temperature equal to 700°C. The ignition of the mixture air/fuel is ensured by an autoignition. The extinction model and turbulence model used in simulations are the default code models.

The numerical simulations are carried out in a rectangular 3D domain with dimensions of 200 m × 200 m × 300 m assimilated to an open ambient environment. These dimensions are obtained from the max-diameter and the max-height of the fireball calculated using the empirical correlations presented in the second section.

3.2 Mesh sensitivity analysis

In the mesh resolution, it is necessary to determine the fire characteristic diameter according to its heat release rate (HRR). This diameter, denoted D^*, is written as [32]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_\infty T_\infty \sqrt{g}}\right) \quad (7)$$

where D^* is the characteristic fire diameter, $\dot{Q}$ is the heat release rate, and c_p is the specific heat.

From obtaining the characteristic diameter, the optimal mesh size of the domain is given by the dimensionless ratio $\frac{D^*}{\delta_x}$, where δ_x is the nominal mesh size.

Based on several experiences, the US Nuclear Regulatory Commission recommends a $\frac{D^*}{\delta_x}$ ratio between 4 and 16 to produce accurate results at a moderate computational cost [18, 39].

In order to model a fireball using FDS, it is important to define the good mesh size. For that, a comparison between experiment data and numerical data using

four mesh sizes is made in **Figure 1(a)** and **(b)**. The different mesh sizes are obtained from the US Nuclear Regulatory Commission recommendation. The numerical simulations are carried out in a rectangular 3D domain with dimensions of 200 m × 200 m × 300 m as mentioned previously.

The comparisons between the experiment and the predictions for the four different meshes are made based on the evolution of the heat flux and the fireball height (cf. **Figure 1**). The heat flux was measured at 30 m over the ground from the projected center of the fireball on the ground under the fireball, and the height was obtained from the fireball center to the ground level. These figures show that the numerical results obtained from the mesh sizes of 0.5 m and 1 m converge with the experimental results, while the results from the mesh sizes of 2 m and 4 m diverge. Moreover, the mesh size of 0.5 m offers more precision than the results obtained with a mesh size of 1 m as shown by the root-mean-square Error (cf. **Table 1**).

From **Figure 1(a)** and **(b)**, the numerical simulation with a mesh size of 0.5 m is more precise but requires a calculation time 50 times greater than the calculation carried out with a mesh size of 1 m (cf. **Table 1**). Thus, by wanting to conciliate precision and optimal calculation time, the mesh size of 1 m will be used for the rest of numerical simulations. This mesh size allows solving the Navier–Stokes equations with a good accuracy. Indeed, with the mesh size of 1 m, the different numerical models such as the turbulence model based on the Deardorff model, the combustion model based on the EDC definition, and the extinction model based on the critical temperature flame are very well calculated for giving a very nice modeling of the fireball. Moreover, taking into account the mesh size
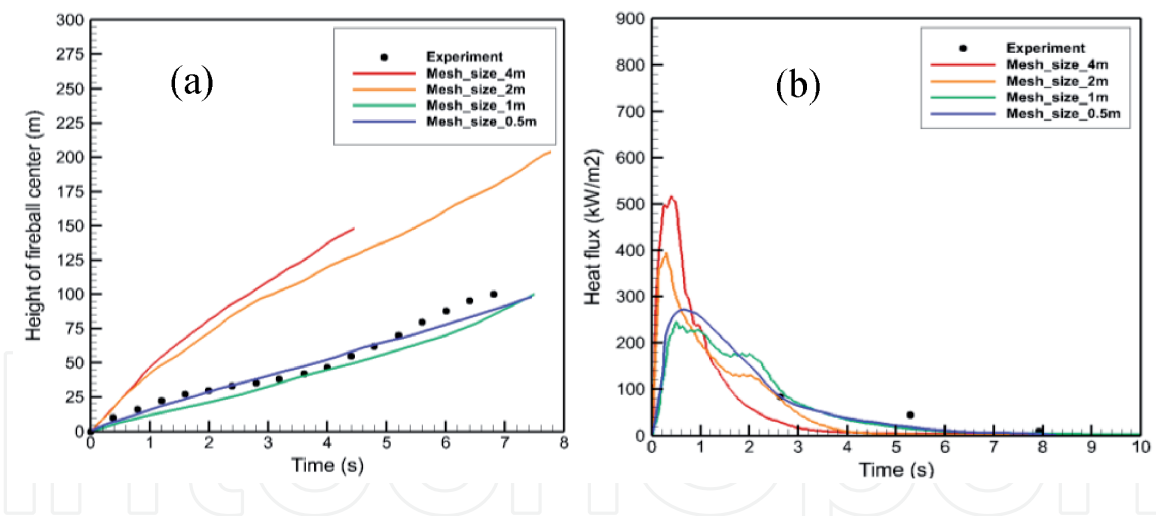

Figure 1.
Mesh resolution on (a) the height of fireball center and (b) the heat flux at 30 m on ground level.

Numerical grid	Number of cells	Root-mean-square error		CPU time (min)
		Height (m)	Heat flux (kW/m^2)	
Mesh size 4 m	187,500	60.22	34.09	2
Mesh size 2 m	1,500,000	59.01	21.56	14
Mesh size 1 m	12,000,000	9.74	16.24	161
Mesh size 0.5 m	96,000,000	5.86	13.23	8000

Table 1.
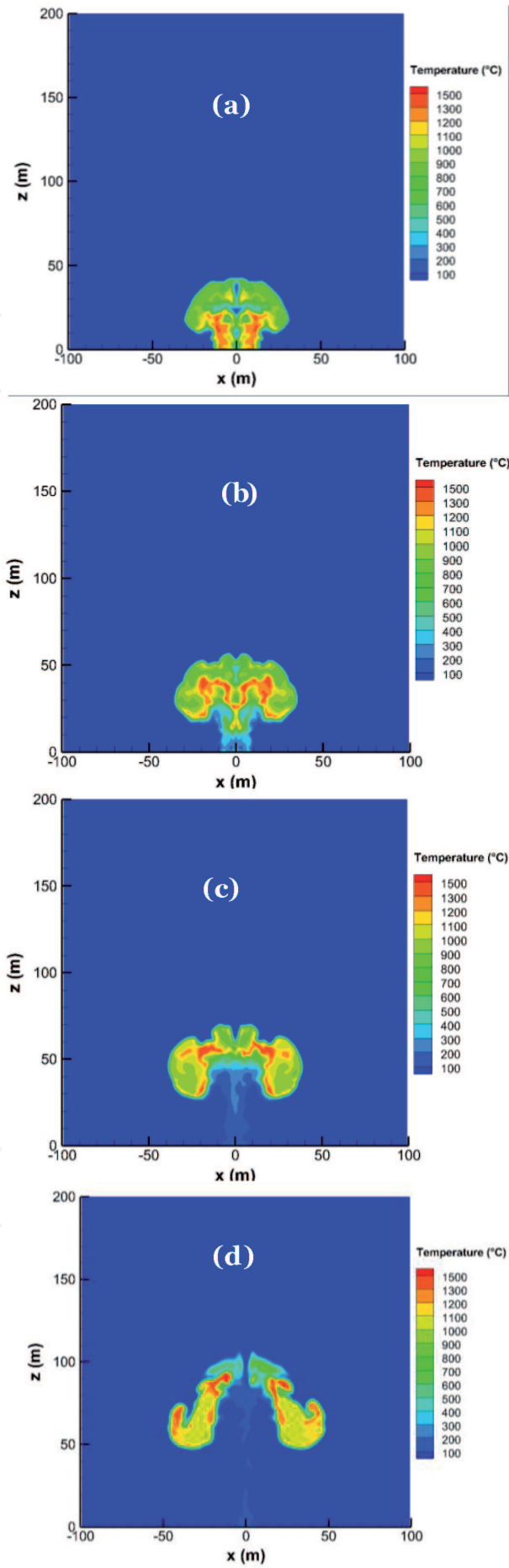*Results of mesh sensitivity analysis.*

Figure 2.
Simulation of the fireball temperature field with mesh size 1 m in the cross-section at (a) 2 s, (b) 3 s, (c) 4 s, and (d) 6 s.

Fireball Characteristics	Experiment	Empirical	Present data	RMSE (Empirical)	RMSE (Present data)
Max-diameter (m)	100	98	101	1.41	0.71
Duration (s)	7.2	7.4	7.8	0.14	0.42
Max-height (m)	100	74	99	18.38	0.71

Table 2.
Comparison between numerical data and BAM test.

of 2 and 4 m, there is an important divergency on the solving of the previous numerical models.

Working with the mesh size of 1 m, **Figure 2(a)–(d)** shows the evolution and the development of the fireball structure at different times (2, 3, 4, and 6 s) after the fuel release to the atmosphere. From these pictures, the evolutions of the temperature field obtained from the numerical modeling highlight the same observations made by Hurley et al. [40]. It is observed that the diameter of the flame increases the height and the time, and Hurley et al. have observed that the diameter of the fireball reaches its maximum at about 6 s with a value of 100 m as diameter. And, by making a comparison with the numerical data, this one agrees with experimental results.

Moreover, considering that the flame temperature of a hydrocarbon fire can approach about 1300°C, it is shown in **Figure 2(a)–(d)** that the predicted field temperature represents the diameter of the fireball during its evolution. In this context, the reactive flows modeled using this mesh resolution come close themselves to the flame dynamics of BLEVE phenomenon.

In conclusion, FDS can predict BLEVE characteristics after a good definition of the mesh size and the fuel release rate. For another case of validation, **Table 2** illustrates the comparison between numerical data and BAM test. In this one, it is observed that the predictions of the parameters such as max-diameter, lifetime, and max-height of the fireball agree with experiment with a better precision than empirical estimates.

4. BLEVE thermal effects: case study for a Hassi R'Mel gas processing plant

From the previous analyses, it has been shown that FDS code is able to simulate the evolution and development of a fireball in comparison with experimental test, considering that it is possible to predict the evolution and thermal effects of a BLEVE in a real installation. In addition, from the numerical results obtained in the previous section, it is necessary to use a nice mesh size in order to make an accurate modeling of a fireball under FDS and a good knowledge of the mass and the release rate of the fuel. Moreover, the definition of a calculation domain that considers the recirculation and the reactive flows during the fireball expansion is very important to justify a good numerical calculation. So, respecting the previous numerical recommendations, it is possible to simulate thermal effects of BLEVE in a real installation such as in Hassi R'Mel Gas Processing Plant.

4.1 Description of the gas processing plant and the ignition source

The gas processing plant studied in this work is defined as the Module Processing Plant 3 (MPP3) of SONATRACH Company at Hassi R'Mel gas field

(located about 550 km south of Algiers). This MPP3-plant consists of three identical gas processing trains that mainly produce natural gas (with a production capacity of 60 million m³/day), LPG, and condensate. **Figure 3** illustrates the configuration of the MPP3-plant. The origin of the explosion is taken at the level of a pressurized propane accumulator D108 located in the MPP3-plant as shown in **Figure 3**.

The choice of the accumulator D108 is based on the opinions of the risk analysts who consider it as one of the most critical systems in the MPP3-plant, which can generate catastrophic BLEVE accidents [41]. **Table 3** summarizes the technical characteristics of the D108 vessel used in our calculation.

4.2 Boundary conditions

The numerical modeling of the MPP3-plant described above is carried out in an open calculation domain of 300 m × 300 m × 360 m. The dimensions of this domain are chosen based on the fireball diameter and height calculated using empirical correlations. The calculations are carried out under atmospheric conditions with a relative humidity of 40% and an ambient temperature of 20°C. The plant configuration is modeled as solid obstructions considering the real equipment dimensions of the three MPP3-plant trains.

The calculations were performed with a time step of 0.01 s and took 2729 minutes with a mesh size of 1 m (i.e., 32,400,000 meshes) using 90 CPUs. The simulation is performed using the default numerical models. The ejection surface was calculated using the approach of Makhviladze et al. [38] as mentioned in Section 3. The origin of the explosion is taken at the level of the D108 as mentioned previously. Using the
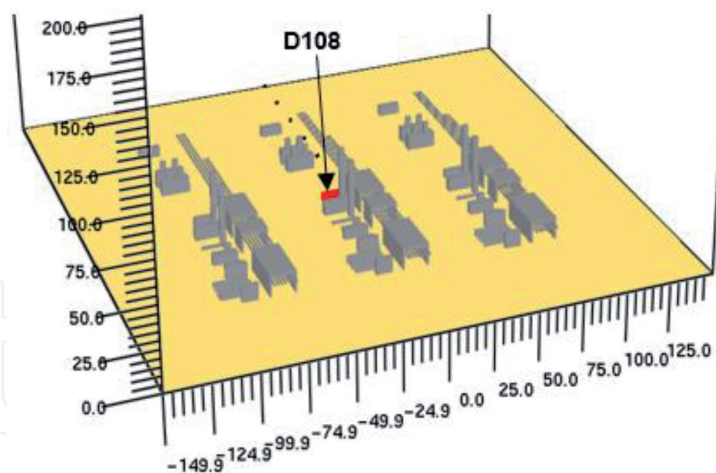

Figure 3.
Numerical MPP3-plant.

Characteristics	Values
Operating temperature (°C)	40
Operating pressure (bar)	14.5
Volume (m³)	50
Propane density (kg/m³)	483.6

Table 3.
Technical characteristics of the accumulator D108.

same modeling approach presented in Section 3, the BLEVE is modeled through the ejection of 24,180 kg of hot propane with a velocity of 100 m/s.

5. Results and discussions

In the previous section, it is shown that the comparison of the predicted fireball diameter and lifetime with the empirical values is similar to the experimental data. However, the predicted height is better than the empirical value in comparison with experiment data.

Considering the real installation, there are no experimental data and so no possibility to compare with empirical values and numerical data. In these conditions, the comparison is made only between the numerical and empirical data based on the evaluation of BLEVE characteristics. Moreover, considering the observations made in the previous section, the results issued from the BLEVE simulation in the MPP3-plant show similar observations. Indeed, in **Table 4**, the predicted fireball diameter and lifetime are like the empirical values, but the empirical height is underestimated by comparing to the predicted value.

Taking into account the comparisons obtained previously, it is possible to say that the evolution and the development of the fireball predicted by FDS in the MPP3-plant would be representative of reality. **Figure 4** shows the simulation of the fireball at two different times in the studied plant. With this simulation, it is possible to follow the evolution of different physical parameters in a spatiotemporal manner such as heat flux, heat release rate, species concentrations, flame temperature, etc. In this paper, only the prediction of heat flux is studied.

Figure 5 presents the comparison between the prediction and the empirical approach based on the evolution of heat flux over time at 50 and 70 m at ground level. It is found that the prediction provides a temporal evolution of the heat flux representative of the reality in comparison with the empirical one which gives a constant value. Indeed, during the first moments, a maximum peak of the heat flux is observed. This maximum value represents the heat flux emitted by the fireball when the latter is near to the ground. With the fireball elevation in height, the heat flux received at ground level decreases. This is represented by the evolution of the heat flux predicted by FDS code. From these comparisons, it is justified that the data provided by the numerical simulation give a more realistic support during a QRA.

Indeed, as indicated in introduction, risk analysis requires knowledge of representative input data of the phenomenon to be studied. Thus, depending on the data, a risk analysis can be well estimated, underestimated, and overestimated. As a result, it is preferable to use the data obtained from numerical simulation in comparison with the data obtained from empirical laws.

Fireball characteristics	Empirical	Present data
Max-diameter (m)	163	174
Duration (s)	12.7	14
Max-height (m)	122	160

Table 4.
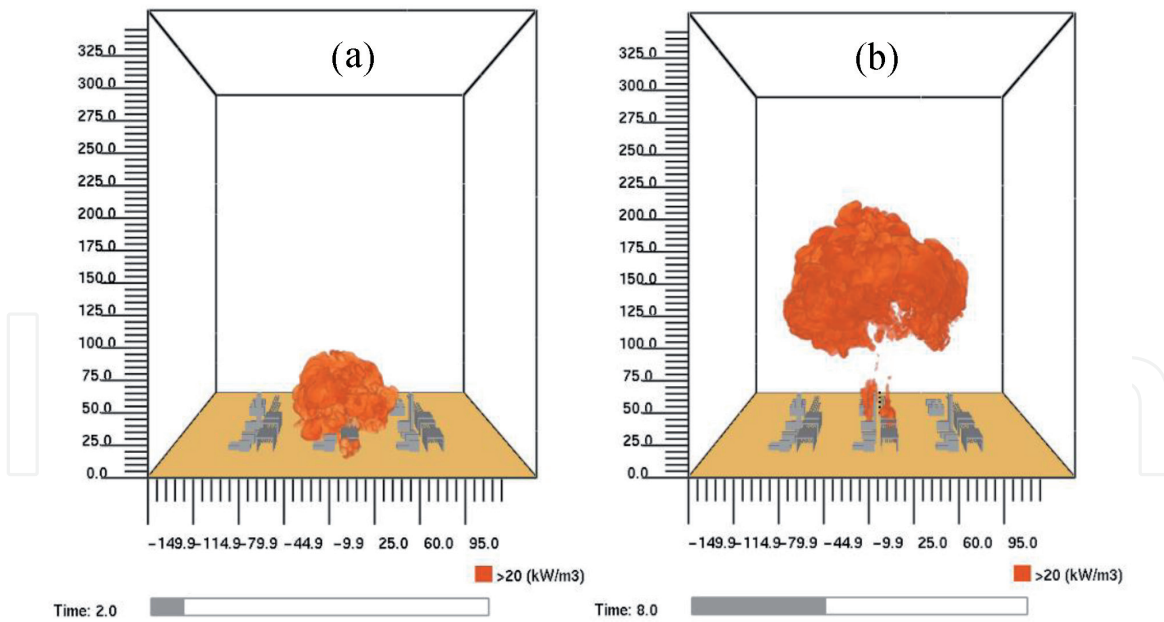*Comparison between numerical and empirical data for MPP3-plant.*

Figure 4.
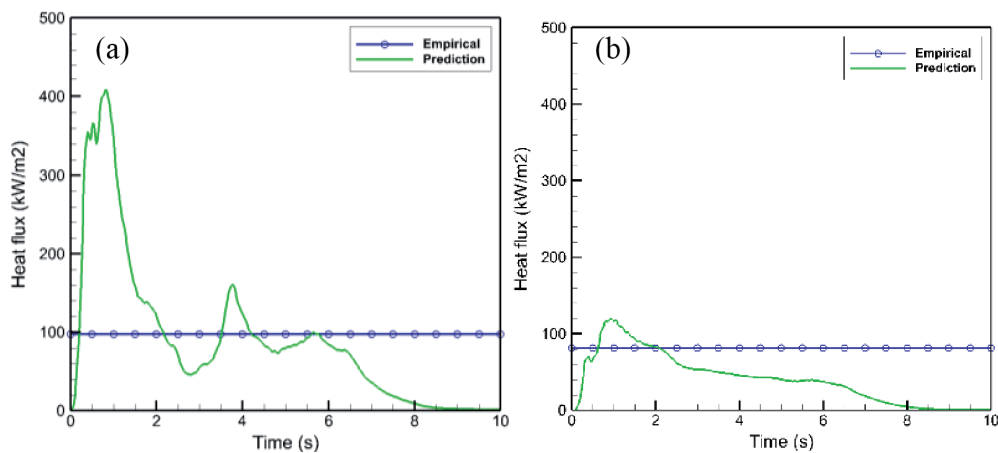*Fireball simulation at (a) 2 s and (b) 8 s.*

Figure 5.
Comparison between empirical and thermal flux prediction at the distance of (a) 50 m and (b) 75 m on the ground level.

In addition to the evolutions of the heat flux presented in **Figure 5**, the same observation is found in **Figure 6(a)** and **(b)**. These figures show the heat flux distribution at 1 s and 4 s in order to better observe the heat flux field over the entire MPP3-plant. With this illustration, it is shown that it is necessary to present the results during the first few seconds. Indeed, considering the heat flux distribution throughout the plant, it is observed during the first instants that the heat flux intensity is important at the explosion source and decreases in the remote zones.

In **Figure 6**, it is observed that the heat flux intensity decreases at the explosion origin and increases in the remote zones with the fireball evolution in terms of diameter and height. This observation is like the reality and is true only for a fireball height less than 70 m.

In conclusion, the BLEVE thermal effects in Hassi R'Mel Gas Processing Plant are well predicted by FDS. In addition, the predictions of FDS give information which allows a better understanding on BLEVE phenomenon. It can be considered also a tool that can be used in a QRA.
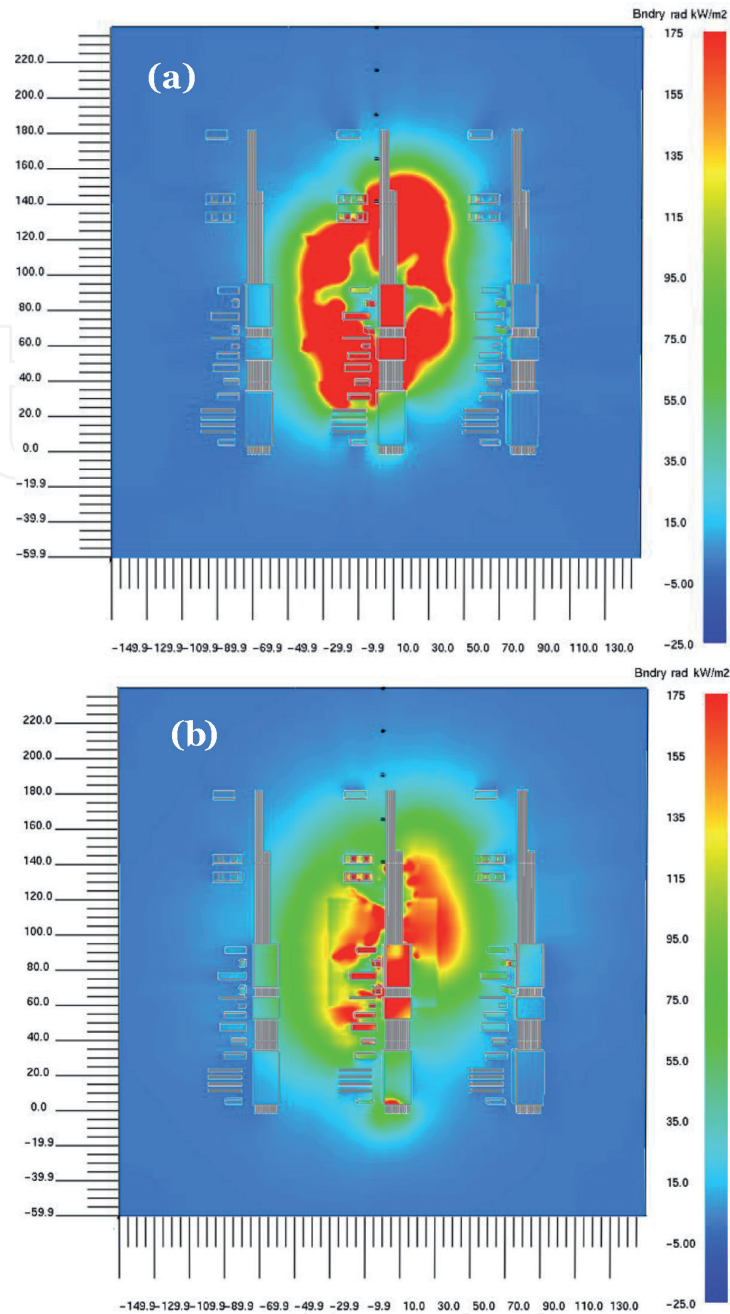
Figure 6.
Thermal radiation contour plot in the x-y plane at (a) 1 s and (b) 4 s.

6. Conclusion

In this chapter, a CFD evaluation of the thermal effects of the BLEVE phenomenon in a real installation is presented. This evaluation firstly required the code validation to correctly simulate the BLEVE characteristics in comparison with the data that come from literature experimental test. Numerical calculations were performed using the CFD FDS code version 6.5.3 with the default numerical models. The results show a good agreement between the predictions and the experiments, justifying a nice capability to FDS to simulate the fireball dynamics with a good accuracy.

After highlighting that FDS can predict the spatiotemporal evolution of a fireball in comparison with an experimental test, a simulation of the BLEVE is performed in a real installation. This involves studying the fireball thermal effects resulting from the explosion of a pressurized propane tank in an Algerian gas treatment unit. The results obtained showed great relevance of carrying out this type of study in

this type of installation. From the numerical data, it is shown that the heat flux reaches a maximum value during the first moments at ground level and decreases with the elevation of the fireball. In addition, comparisons between prediction and empirical models, based on heat flux evolution, show that prediction is representative of reality compared to empirical models. Thus, for a risk analysis in this type of installation, it is preferable to use the numerical approach.

Moreover, the current results can be considered as a first step to make a modeling of the BLEVE phenomenon, and in order to improve the global description of this phenomenon, it will be necessary to consider, in a next work, the container disintegration in order to model the complete BLEVE process.

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