Nuclear Engineering and Design 318 (2017) 147–162

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Numerical simulations of liquid spreading and fires following an aircraft impact

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HIGHLIGHTS

- Methodology for simulating fires resulting from aircraft impact was developed.
- The methodology was validated using experimental data.
- Large scale simulations of aircraft impact on a nuclear island were conducted.
- The fraction of fuel available for subsequent fires was found to be significant.
- The pooling fraction was strongly affected by impact geometry.

ARTICLE INFO

Article history:
Received 22 July 2016
Received in revised form 4 April 2017
Accepted 7 April 2017

Keywords:
Fireball
Plane crash
Physical separation
Fuel pooling
Nuclear power plant

ABSTRACT

In this paper, we present a methodology for predicting the spreading and combustion of liquid fuel released from an aircraft impact. Calculations were done with Fire Dynamics Simulator, and the aircraft impact was modeled as a spray boundary condition. The spray boundary condition was developed and validated by experiments using water-filled missiles. The predicted liquid front speeds were compared with water spray front propagation data, and the predicted lifetimes and diameters of fireballs were compared with experimental correlations. A full-scale simulation of the aircraft impact on a nuclear island was performed. The simulation results were used to assess the adequacy of physical separation in the case of aircraft impact. We concluded that 10%–20% of the fuel involved in the crash will accumulate in pools around the building.

1. Introduction

Safety analyses of nuclear power plants (NPPs) have long included aircraft impacts. Initially, the impact was envisioned to be from a small aircraft or possibly a fighter plane. Following the September 11 terrorist attacks on the World Trade Center in 2001, these analyses have been extended to assume the impact of a large commercial aircraft (e.g. NEI 07-13, 2011).

Such an aircraft can damage safety-related structures and components through mechanical impact and fire. Fires induced by an aircraft impact may influence the NPP by three different mechanisms. Initially, a large fireball is created by the fuel cloud erupting from the breaking fuel tanks. This fireball has a duration of few seconds and can be hundred meters in diameter. The most serious threat from a fireball to its surroundings is thermal radiation. The dose of thermal radiation received by a target is dependent on the size and duration of the fireball.

Only a fraction of the fuel carried by the plane will burn in the initial fireball. The remaining fraction of the fuel will accumulate and burn in pools near the aircraft impact position. The size and burning rate of the pool fire depend on the geometry, properties of the roof and ground surfaces, and possible fire suppression activities.

The third mechanism involves the penetration of aviation fuel inside the plant through openings. These openings may exist beforehand (e.g., for ventilation) or be created by the aircraft impact. Even if the amount of penetrated fuel is small, it can cause a rapid ignition of existing fire loads to result in internal fires.

The literature on aircraft impacts involving fuel is scarce. Early test series by the Federal Aviation Administration (FAA) and National Advisory Committee for Aeronautics (NACA) using belly-landing aircraft demonstrated that fuel spilled from ruptured tanks forms a fine mist cloud that can be ignited by several sources

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http://dx.doi.org/10.1016/j.nucengdes.2017.04.012
0029-5493/

(Pinkel et al., 1952; Ahlers, 1977; Johnson and Garodz, 1986). Experiences from numerous real crash incidents such as the September 11 terrorist attacks support this observation. Luther and Müller (2009) analyzed the film footage of aircraft crash fireballs. They discovered that these fireballs are very similar to those resulting from boiling liquid expanding vapor explosions (BLEVEs). However, none of the analyzed accidents included an impact on a rigid vertical structure, such as modern NPPs.

Several experimental correlations exist for determining the diameters and lifetimes of fireballs resulting from BLEVEs. Abbasi and Abbasi (2007) gave an excellent review of the hand calculation methods used to model BLEVEs. These methods can also be used to analyze fireballs from aircraft impacts. However, they cannot be used to estimate the fraction of unburnt fuel.

Baum and Rehm (2005) proposed a model for the global energy release rate of fireballs. They calibrated their model by comparison with videos of the WTC fireballs and used it to estimate the fuel involved in the subsequent fires. They found that most of the fuel carried by the airplanes did not burn in the initial fireball and was available for fires that destroyed the buildings. This result was likely to have been a consequence of the airplane penetrating the outer wall of the building.

Considering the complexity of the three above mechanisms, their analyses cannot rely on empirical formulas derived from idealized situations but on transient numerical simulations of the fuel spray and combustion.

Fireballs resulting from vertical fuel gas releases were investigated numerically by Makhviladze et al. (1998). Makhviladze et al. (1999) extended this model to investigate two-phase fuel releases from pressurized containers of liquefied gas. Their model solves two-dimensional Favre-averaged Navier–Stokes equations by using the standard k-ϵ turbulence model and infinitely fast one-step reaction. The dispersed phase is treated in a Lagrangian fashion. They assumed a monodisperse droplet size distribution with the initial velocities of the droplets derived from Bernoulli's law. They compared the predicted lifetimes of fireballs with the experimental correlation of Roper et al. (1991), and they compared the transient shapes and sizes of the fireballs with the experiments of Hasegawa and Sato (1978). Makhviladze and Yakush (2005) used this model to analyze total loss of containment scenarios for BLEVEs. They also investigated the overpressures that would occur in such events.

Yakush and Makhviladze (2005) compared Reynolds-averaged Navier–Stokes (RANS) and large eddy simulation (LES) predictions of the fireball lifetime with the experimental correlation of Roper et al. (1991). They used Fire Dynamics Simulator (FDS) version 4 for the LES calculations. FDS was found to underestimate the fireball lifetimes. The fuel release was modeled with a gas inflow boundary condition. Hu and Trouve (2008) used a modified version of FDS to investigate deflagrations of premixed fuel vapor clouds. They did not consider high speed jets. Instead the vapor clouds were created by slowly injecting gas to the simulation domain. Luther and Müller (2009) used FDS version 5 to determine the spreading and extent of the fireball around a generic NPP. They also modeled the fuel insertion by using a gas inflow boundary condition.

In the above fireball simulations, the fuel inlet boundary condition consisted of either a vertical spray or injection of fuel gas from a boundary patch. Initial velocities of the gas and droplets have been based on, for example, the theoretical calculations of flash evaporation. When multiphase models have been used, droplet sizes have been assumed to be monodisperse. The possibility of fuel droplets raining out of the fireball has usually been neglected. This may be because of the highly volatile liquids such as liquefied natural gas (LNG) and propane that are being considered.

Analysis of footage of real aircraft crashes and the results of Baum and Rehm (2005) indicated that, in aircraft crashes, a significant amount of the fuel may not be burned in the initial cloud. In the case of an aircraft crash, part of the fuel released is traveling towards the ground and walls. The fuels involved are also less volatile. This means that fuel droplets may rain out of the burning cloud.

In some of the published analyses, such as that of Jeon et al. (2012), the amount of fuel burning as a pool has simply been assumed to be equal to the amount of fuel carried by the aircraft. This kind of assumption is conservative and well-justified if better information is not available. Predicting the amount of fuel available for pool fires requires accurate modeling of the fuel sprays from ruptured tanks of liquid fuel.

Brown et al. (2012) coupled a transient dynamics code Presto to a low-Mach number fire code Fuego in order to predict the liquid dispersion from a high speed impact. They used Smoothed Particle Hydrodynamics (SPH) to predict the motion of liquid within the tank on impact. The particles from the SPH solution were then transferred to the fire code once the distance between the particles dropped under a certain threshold level. They found that their model was able to reasonably reproduce the quantified results of the experiments of Jepsen et al. (2009). These results consists mainly of liquid dispersal patterns. Brown et al. (2014) noted that the method still lacks validation, especially concerning the evolution of droplet size.

The objective of this work was to develop and validate a computational fluid dynamics (CFD) methodology for predicting the spreading and combustion of liquid fuel released upon an aircraft impact. The model for liquid release is based on the experimental work of Hostikka et al. (2015). The experimentally determined droplet sizes and spray velocities were used to determine realistic spray boundary conditions for liquid insertion. We focused on the threat posed by the initial fireball and amount of fuel that collects on the target surfaces. The subsequent combustion of the pools was not considered.

This paper is organized as follows. First, the numerical model is presented. Next, the boundary condition describing the fuel release is presented with experimental data. The validation of the numerical model against experiments and correlations is given next. First, the shape and size of the droplet cloud predicted by the model is qualitatively compared with photographs from the Sandia F-4 impact experiments. The predicted spray front velocities are then compared with experimental data. The predicted lifetimes and diameters of the two-phase fireballs are compared with the experimental correlations. Finally, we present the results from a full-scale simulation of an aircraft impact on a nuclear island. The simulation results were used to evaluate the adequacy of physical separation. We also examine the fraction fuel that will burn as a pool.

2. Computational method

All simulations in this study were done by using FDS (McGrattan et al., 2013a, 2012; McDermott, 2014), which is an LES code that solves a form of the Navier–Stokes equations appropriate for a low-speed and thermally driven flow with an emphasis on smoke and heat transport from fires. The governing equations for momentum transport are discretized by second-order central finite differences on a Cartesian staggered grid. A two-stage explicit Runge–Kutta method is used for time-stepping. Radiative heat transfer is included in the model via the solution of the radiation transport equation (RTE) for a gray gas. The RTE is solved by a finite volume method. The governing equations are presented here for completeness. More detailed descriptions of the model and numerical procedure are given by McGrattan et al. (2013a, 2012) and McDermott (2014).