ISSN 1648-7788 / eISSN 1822-4180

VILNIUS TECH
Vilnius Gediminas Technical University

AVIATION

2023
Volume 27
Issue 3
Pages 131–140
https://doi.org/10.3846/aviation.2023.19729

LIQUID NITROGEN INJECTION INTO AVIATION FUEL TO REDUCE ITS FLAMMABILITY AND POST-IMPACT FIRE EFFECTS

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Article History:
received 12 August 2022
accepted 25 January 2023

Abstract. The finite volume method was used to study the characteristic of contaminated aviation fuel with the aim of reducing its flammability and post-impact fire. The flammability levels between pure Jet A-1 and contaminated Jet A-1 are compared using their flashpoints and fire points before and after the introduction of Liquid Nitrogen. Upon heating different mixing ratios (4:1, 3:1, and 2:1), results are analyzed to identify the best volume ratio exhibiting the highest reduction in flammability. Analysis shows that the mixing ratio of 2:1 not only froze but increased the flashpoint of the mixture from (48 ˚C–50 ˚C) to 64 ˚C. For the mixing ratio of 3:1, there was a rise in flashpoint to about 56 ˚C and partial freezing was seen at the topmost surface. At a mixing ratio of 4:1, it was observed that the effect of liquid nitrogen on Jet A-1 was minimal leading to a slight rise in its flash point (50 ˚C). Thus, liquid Nitrogen had a substantial effect on the flammability and flash point of Jet A-1 when mixed in the ratio (2:1) with a freezing time of 30 seconds and an unfreezing time of 17.5 minutes. Hence, Liquid Nitrogen can be used for the flammability reduction of Jet A-1.

Keywords: post-impact fire, flashpoint testing, CFD analysis, fire safety, contamination, FEM.

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Introduction

Investigations show that a series of fatalities incurred during an aircraft accident is usually due to an aircraft explosion, aircraft fire, damage to the airframe, phase of flight lighting condition, weather condition, air temperature, landing surface, etc. To understand the epidemiology of death on the battlefield, a panel of the military medical team reviewed photographs, autopsy, and treatment records for all special operation forces who died between October 2001 and November 2004. In 82 cases captured, it was recorded that death due to explosions was 43%, gunshot wounds, 28%, aircraft accidents, 23%, and blunt trauma 6%.

A report of the factors associated with pilot fatalities in aircraft crashes in Alaska mentioned that one of the most frequent ones are crashes involving post-impact fires (North Atlantic Treaty Organisation, 2004).

Aviation safety information system (ASIS) also showed aircraft accident statistics between 1976 to 2002 which involved 13,806 small aircraft in Canada. As a follow-up, the Transport safety board (TSB) documented that post-impact fire (PIF) had occurred in 521 or 3.8% of these accidents. The 13,806 accidents that occurred resulted in 3311 fatalities and 2217 serious injuries (Transportation Safety Board of Canada, n. d.). The post-impact fire accounted for 728 (22%) fatalities and 231 (10%) of all serious injuries. Based on this, it was observed that the fatalities of post-impact fires were five and a half times greater, while the rate of serious injuries was nearly tripled when compared to the fatality rate of all accidents. This is graphically detailed in Figure 1.

The extent to which post-impact fire contributes to injuries and fatalities in small aircraft accidents has been documented in other studies. The death certificates obtained from the National Centre for Health Statistic for all aviation-related accidents during the years 1980 to 1990 were reviewed by (Li & Baker, 1997) and it was determined that burns were recorded as the immediate cause of death in approximately 4% of the fatalities. It was also noted that the death certificates described only post-mortem injuries, with the result that the effect of post-impact fires may have been underestimated.

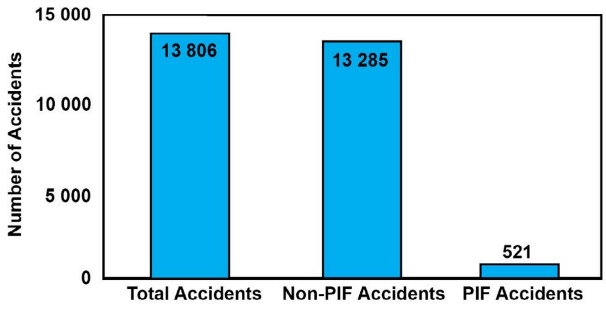

Figure 1. Comparison of non-post-impact fire and post-impact fire small aircraft accident, 1976–2002 (source: Transportation Safety Board of Canada, 2006)

Bensyl et al. (2001) examined work-related accidents in Alaska between 1990 and 1999 and concluded that post-impact fire was the strongest predictor of fatalities, they also estimated that the odds of death occurring were 14 times greater when a fire occurred after a crash than when it did not.

Volatile liquid fuel is the combustible material of greatest significance in post-impact fire accidents. Considering the propensity for rapid propagation and the catastrophic consequences of fuel-fed post-impact fire, the most effective defense against post-impact fire is to prevent the fire from occurring at impact, either by containing the fuel or preventing ignition or both. On June 5 1970, an Air Canada 621 crashed in one of the most devasting air mishaps in Canada's history. With 109 fatalities and zero survivors one would imagine the role liquid nitrogen would play give the circumstances (Wikipedia Contributors, 2023a).

In the test carried out by the National Advisory Committee for Aeronautics (NACA) to determine escape time by measuring ambient and radiant temperatures in crashed and various burning fixed-wing aircraft, it was estimated that the escape times from large aircraft post-impact fires, based on aircraft skin burns and human tolerance to heat, varied from 53 seconds to 220 seconds, with the average being 135 seconds; while in small aircraft, it was 17 seconds (Hurley & Vandenburg, 2002). These data show that, when a post-impact fire occurs and an occupant is prevented from self-exiting a small aircraft, there is a high risk of such occupant sustaining a fire-related injury or fatality.

Reducing the flammability of aviation fuel has become a major concern in the aviation industry. Over the years, air crashes have resulted in the loss of lives and property. Following a series of fuel-related accidents between 1990 and 2001, the Federal Aviation Administration (FAA) re-examined fuel tank security. In its "Most Wanted Transportation Safety List for 1997", the National Transport Safety Board (NTSB) included "Explosive Fuel Tank Mixture in the Transport Category of Aircraft" (Gupta, 2015).

These fatalities are mostly caused by the blaze spread rate of aviation fuel after impact. For high flashpoint fuels such as Jet A, the environmental and bulk fuel temperatures are usually lower than the flash point temperature. Consequently, the flame spreading rate on a liquid surface is much smaller than that for low flashpoint fuels such as gasoline (Bossert et al., 2003).

Hollow Fiber Membrane (HFM) Gas Separation technology provides the gas industry with a cost-effective and efficient method for gas separation. The principle of selective permeation across the membrane wall is used to separate gases. HFMs are extremely small (on the scale of a human hair) and are normally made by grouping huge numbers of them into hollow tubes to compress as much surface area as possible into the lowest volume (Burns & Cavage, 2001).

However, under dynamic crash conditions, these fuels are dissolved moderately or largely from broken tanks into a high-speed airflow, they break up into fine droplets, thereby forming a highly flammable mist. This fuel mist is easily ignited by one or more of the numerous transitional ignition sources, including friction sparks, hot motor parts, etc. The spread of fire from the temporary source to the point of a fuel is rapid and a large ball is developed in the fuel mist area. The fireball serves as a large ignition source that ignites pools of liquid fuel around the aircraft as it decelerates to a stop. In general terms, the three key elements of Combustion are fuel, air, and an ignition source. Fire prevention methods attempt to separate one key element of fire from the other two. Since air is ubiquitous, the separation of it from the other two is questionable except in specific situations such as in-flight inerting of fuel tanks. This leaves the separation of fuel from the other two or the ignition source from the other two. Fuel separation has taken two general forms, a long-running attempt of developing an anti-misting agent for jet fuel (AMK) and the introduction of inert gas into the jet fuel (Liquid Nitrogen) (Bossert et al., 2003).

Figure 2 shows the post-impact fire safety process and instances it can be deployed to mitigate hazards. A variety of systems has been investigated for the reduction of flammability, this process includes, On-Board Inert gas separation (OBIGGS), this method involves ullage inerting, which entails pumping an inert gas, such as nitrogen, into the ullage, to reduce the oxygen concentration therein. The Nitrogen can be obtained from cryogenic storage bottles on board the aircraft, or the OBIGGS (Gupta, 2015).

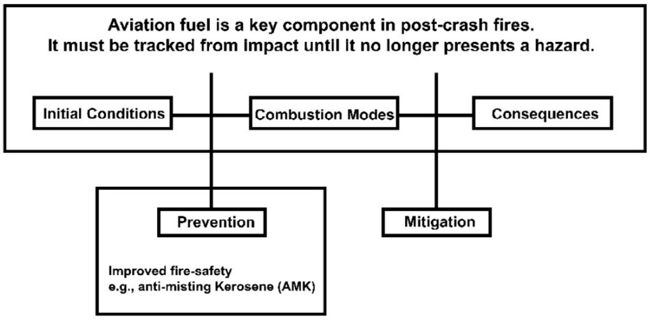

Figure 2. A schematic of the post-impact fire safety process (source: Tieszen, 1997)

Nitrogen generation system (NGS), flammability reduction system (FRS), and fuel tank inert system (FTIS) (Evosevich & Jojič, 2015).

Akhtar (2010) investigated one of the methods for flammability reduction using Air separation modules (ASMs). In his investigation, he configured his design to receive air feed from the pressurized air source while a fuel tank on board the aircraft was used to receive Nitrogen-enriched air from the air separation module. Careful observation and evaluation have shown that known pressurized air sources available on aircraft, such as engine bleed air, may be contaminated with various gases (including hydrocarbon gases) and liquid or solid aerosols of various sizes. Larger particles may also be present. More particularly, engine bleed air has been demonstrated to contain residues and degradation products from jet fuel, engine lubricating oil, hydraulic fluid, de-icing agents, and other contaminants present in the atmosphere, on the ground, and at altitude. Predominant contaminants are hydrocarbons containing only hydrogen and carbon, but other hydrocarbons and other contaminants, such as aldehydes, ketones, acids, and other gases may be present. According to Akhtar (2010), gas separation membranes, in general, are very susceptible to large hydrocarbon molecules, and degradation products.

Air separation modules (ASMs) known for use in Aerospace contain hollow fibre membranes, which permeate oxygen through the membrane preferentially to nitrogen. The molecules that do not permeate are retained and are called nitrogen-enriched air.

Based on Akhtar's (2010) submission, some of the disadvantages of ASMs involve the loss of performance due to contamination and natural relaxation for the fibre, also in some cases, ASMs exhibit decreased service life, also fibre pores of the membrane can be plugged by particulates. Liquids can coat membranes, thereby causing polymer swelling or impaired membrane integrity. Polymer solvents could contribute to the delamination of a polymer separation layer and could lead to compaction or fibre deformation.

Tieszen (1997) also studied the impact of aircraft as a series of processes involved in fuel dispersal. The study reported that from the time of impact until the aircraft motion is terminated, tremendous energy is dissipated. During a routine landing, this energy is dumped into the brakes, tires, and through thrust reversers into the air. In a crash, this energy can further be dumped by abrasion of the fuselage or other parts that are skidding along the ground or in large-scale deformation upon impact with a solid object, all of which can produce either sparks or a hot surface for ignition. At sufficiently high impact energies, a fuel tank may fracture and begin to leak. This loss in control of geometry results in the process of fuel dispersal.

Dispersal also occurs as the force balance changes on the fuel emerging from the tank. The fuel stream is subject to a free, pressure boundary just outside the damaged tank. During slide out, there is a relative motion between the aircraft and the surrounding air. The primary goal of the investigation was to develop anti-misting kerosene.

Crash survivability and crashworthiness issues generally have received much more attention in military aviation than general aviation operations and have distinctly influenced crash dynamic patterns and most probably altered injury patterns as well. Research also indicates that aircraft fire is an important factor threatening occupant survival in air carrier crashes and that about 20% of aviation deaths which occurs from aircraft fire crash are preventable given the use of better restraint systems (Wiegmann & Taneja, 2003).

It is also important to know about jet fuel. Jet fuel, often known as aviation turbine fuel (ATF), is a type of aviation fuel used in planes with gas turbine engines. It has a color range of colorless to straw-colored looks. Jet A and Jet A-1, which are produced to a defined worldwide specification, are the most used fuels in commercial aviation. Jet B, which is used for its improved cold-weather performance, is the only alternative jet fuel routinely used in civilian turbine-engine-powered flying (Wikipedia contributors, 2023b). Also, a third choice was gasoline, but it was unappealing due to its excessive fuel consumption. Kerosene or kerosene and gasoline combinations were also used (Chevron, 2007).

Investigations have shown that a series of fatalities incurred during aircraft accidents is because of aircraft explosions, aircraft fire, damage to the airframe, phase of flight lighting condition, weather conditions, air temperature, and landing surface; they also estimated that the odds of dying were 14 times greater when a fire occurred after a crash than when one did not (North Atlantic Treaty Organisation, 2004).

However, the commonality among all the systems involves reducing the oxygen content of fuel tank ullage by feeding inert gas into the fuel tank. However, this system becomes less effective in cases of post-impact fire, because of exposure to an uncontrollable volume of oxygen in the atmosphere since the system is designed to control the amount of oxygen available to the fuel. The most important parameter affecting the flammability of aviation fuel is the temperature (Akhtar, 2010).

Henshaw et al. (1953) conducted experiments by holding liquids in a cryostat mounted on the specimen table of the spectrometer. Also, one of such cooling apparatus was described in Umrath (1974) is much easier to handle. An inner cooling bath is surrounded concentrically by a second, outer bath both containing liquid nitrogen.

The liquid nitrogen is to be injected only when the pilot considers the aircraft irrecoverable. This will alter the chemical structure of unused aviation fuel in the tank before a crash. The idea is to reduce flammability and its post-impact fire effects long enough for a rescue mission. Nitrogen was first liquefied at the Jagiellonian University on 15 April 1883 by Polish physicists Zygmunt Wróblewski and Karol Olszewski (Tilden, 1899). Liquid nitrogen is commercially manufactured via cryogenic distillation of liquified air or by pressure swing adsorption of pure nitrogen extracted from the air. Filtered air is compressed to high pressure using an air compressor; the high-pressure gas is then cooled to ambient temperature and allowed to expand to low pressure (Almqvist, 2003).

The purpose of the research "Liquid nitrogen injection into aviation fuel to reduce its flammability and Post-Impact Fire Effects" is to increase the chances of survival in civil aviation in the event of an impending and irrecoverable crash. Unlike solid particle and free water contaminants that are detrimental to the aircraft fuel system and engine which in turn compromises safety, a liquid nitrogen as an added substance will go a long way in mitigating the effects of post-impact fires (Stevens et al., 2012).

1. Methodology

The main task of the research focuses on analyzing the effect of Liquid Nitrogen on the flammability, flash point, and temperature of aviation fuel in the event of a crash. The infused liquid nitrogen fuel forms a crystalline solid which on impact breaks into smaller crystals thereby increasing the flash point and decreasing the flammability of aviation fuel. When the infusion occurs, the spread of fire post-impact is controlled, thereby increasing the rate of survival, and reducing damage.

A series of experimental tests was carried out such as the flash point test, rate of freezing, and de-icing test, at varying mixture ratios to observe and discover the most suitable fuel-to-nitrogen mix proportion.

The flash point and fire point tests were carried out by placing jet A-1 on a heating source before the infusion of liquid nitrogen at different quantities in a beaker and observations were made. The same experiment was carried out on the mixture (infusion of liquid nitrogen to Jet A-1) and different mixing ratios were also placed on a heating source.

Results comparisons were carried out and the best and most sufficient mix ratio was noted.

The rate of freezing and de-icing experimental analyses was carried out on the infusion of liquid nitrogen, using a thermometer and stopwatch to check and analyze the freezing and de-icing times.

This research involves both laboratory and fluid dynamics analyses using the finite volume method. It involves the following processes:

1. Documentation of Flashpoint and Fire Point Validation of Jet A-1 aviation fuel.
2. Liquid Nitrogen Injection into Jet A-1 aviation fuel at various ratios (1:1, 1:2, 1:3, 1:4).
3. Documentation of Flashpoint and Fire Point Validation of contaminated Jet A-1 aviation fuel.
4. Documentation of the rate of freezing.
5. Documentation of the rate of de-icing.

1.1. Experimental set-up

A measured quantity of Jet A-1 poured into a beaker was placed on a heating source. The heating source having a regulatory increment of 10 ˚C was set to an initial temperature of 30 ˚C, where there was an observable increase in the temperature of jet A-1 measured by the thermometer, a fire source was introduced across the beaker, as the temperature was varied from 30 ˚C to 60 ˚C. Flashfire was observed from a range of 48 ˚C to 50 ˚C, whereby an observable fire sustains on the Jet A1 in the beaker at a temperature of 51˚C. The experiment was repeated, and the flashpoint was gotten to be from 48 ˚C to 50 ˚C, while the fire point was gotten to be 50 ˚C. It was ensured that the beakers and the bowls used for the experiment were properly cleaned, to prevent any form of interference from the external air source, and protective gears were worn when introducing the fire source to the Jet-A1 samples.

1.2. Experimental procedure for contaminating Jet A-1

In the experimental setup, a sample of liquid nitrogen was introduced into the sample of Jet A-1 at different volume ratios of 1:1, 1:2, 1:3, and 1:4. A volume of 20 ml of Jet A-1 was measured which represented a volume ratio of Jet A-1. This quantity of Jet-A1 was then poured into a tin container, thereafter, the temperature of the sample was taken and documented as the initial temperature of the Jet A-1 before the process of injecting liquid nitrogen. A volume of 20 ml of liquid nitrogen was measured which represented a volume ratio of liquid nitrogen. This sample of liquid nitrogen was poured into the container housing the sample of the Jet A-1 immediately after the timing started.

Figure 3 shows the outcome of the mixture. This mixture's time rate of freezing was measured with a stopwatch, after which the thermometer was used to measure the final temperature of the mixture, and the observations from the mixture were documented. This procedure was repeated for all the volume ratios of the mixture and the observations made were recorded.

1.3. Flashpoint and fire point validation of contaminated Jet A-1 aviation fuel

In this experimental setup, the sample of the mixture of Jet A-1 and liquid nitrogen (contaminated fuel) from experiment two was poured into the beaker and was then

Figure 3. Contaminated JET A-1 aviation fuel (source: Authors, 2022)

placed on the heater. The heating temperature was thereafter varied between the derived flashpoint range from Experiment 1, i.e., between 48 ˚C and 50 ˚C. A fire source was subsequently passed across the sample and the observations were recorded. The temperature of the sample was then varied from 50 ˚C to 60 ˚C by an increment of 10 ˚C, which was measured using a thermometer. In the process of varying the temperature of the samples, a fire source was introduced across the samples at different temperatures, and the observations from the experiment were documented. This procedure was repeated for all the volume ratios of the mixture.

However, it is important to know what a flash point is, when provided an ignition source, a volatile material's flash point is the lowest temperature at which its vapours ignite. The auto-ignition temperature, which produces spontaneous ignition, is commonly mistaken for the flash point.

1.4. Computational fluid dynamic analysis (CFD)

Computational Fluid Dynamics (CFD) is a numerical method that is used to simulate physical problems using governing equations. This method can be used to investigate design approaches without creating a physical model and can be a valuable tool in understanding the conceptual properties of new mechanical designs.

For this analysis, a rectangular cavity of 0.5 m by 0.1 m with a depth of 0.1 m was used to depict an aircraft fuel tank.

1.5. Mathematical formulation and turbulence models

In all flow scenarios, a Fluent solver solves the continuity and momentum equations. For multiphase flow situations, additional equations are solved.

The continuity equation can be cast as follows:

$$\frac{\partial p}{\partial t} + \nabla \cdot \left(\rho \vec{\upsilon}\right) = S_m. \tag{1}$$

Conservation of momentum:

$$\frac{\partial}{\partial t}\left(\rho v\right) + \nabla \cdot \left(\rho v v\right) = -\nabla \cdot \left(\tau\right) + \rho g + F. \tag{2}$$

Where the stress tensor is defined by:

$$\tau = \mu\left[\left(\nabla v + \nabla v^T\right) - \frac{2}{3}\right]\nabla \cdot vl. \tag{3}$$

Conservation of energy:

$$\frac{\partial}{\partial t}\left(\rho T\right) + \nabla \cdot \left(v\left(\rho E + p\right)\right) = \\ \nabla \cdot \left(k_{eff}\nabla T - \sum{}_j h_j J_j + \left(t_{eff}, v\right)\right) + S_h. \tag{4}$$

1.6. The realizable $k - \varepsilon$ turbulence model

This model makes use of two independent continuity equations to determine turbulence velocity and length scales (Nigam et al., 2017):

$$\frac{\partial}{\partial t}\left(\rho k\right) + \frac{\partial}{\partial x_j}\left(\rho k \upsilon_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu t}{\sigma k}\right)\frac{\partial k}{\partial x_j}\right] + \\ G_k + G_b - \rho\varepsilon - Y_M + S_k. \tag{5}$$

$$\frac{\partial}{\partial t}\left(\rho \varepsilon\right) + \frac{\partial}{\partial x_j}\left(\rho \varepsilon \upsilon_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu t}{\sigma \varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \\ \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S\varepsilon, \tag{6}$$

where: $C_1 = \max\left(0.43, \frac{n}{n+5}\right)$;

$$n = S\frac{k}{\varepsilon}; \\ S = \sqrt{2S_{ij}S_{ij}}. \tag{7}$$

The constants in Equations (5)–(7) are stated as follows:

$$C_{1\varepsilon} = 1.44, C2 = 1.9, \sigma_k = 1.0, \sigma_\varepsilon = 1.2. \tag{8}$$

1.7. Boundary conditions

The cavity itself should be given wall conditions as shown in Table 1. Ensuring properties of the geometry is important to achieving a workable solution.

Table 1. Boundary conditions (source: Authors, 2022)

Input	Value
Flow Velocity (V)	0.6 m/s^2
Density of Fluids	1 kg/m^3 0.00016065 kg/m^3
Model Used	Multiphase (Volume of fluid) k-realizable Energy
Fluids	Jet A Nitrogen liquid
Operating Temperature	25 K 77 K
Operating Pressure	101325 pascals
Reynolds Number	3 × 105
Area	0.05 m^2
Viscosity	1.7894 × 10-5 kg/ms 806.08 kg/ms
Volume Fraction	1
Wall Temperature	373 k

Reynolds number, expressed by equation (9) below was used to calculate the velocity of liquid nitrogen being introduced into the cavity that contained Jet A-1.

$$\mathrm{Re} = \frac{\rho V1}{\mu}. \tag{9}$$

2. Result of the research

The analyses of the various experiments are tabulated and their variations with temperature and volume ratio are discussed below.

2.1. Flashpoint and fire point test

Table 2 and 3 as presented below shows findings of Experiments 1 and 2 respectively. Both experiments detail the temperature variation of two measured quantities of Jet A-1 relative to the flashpoint and fire point for a temperature range of 30 ˚C and above for the current research.

2.1.1. Experiment 1

Table 2. Test one of flash point and fire point (source: Authors, 2022)

Initial value (˚C)	Flash point	Final value (˚C)	Flash point
30.0	No Flash	39.0	No Flash
31.0	No Flash	40.0	No Flash
32.0	No Flash	44.0	No Flash
35.6	No Flash	50.0	Flash Point

2.1.2. Experiment 2

Table 3. Test two of flash point and fire point (source: Authors, 2022)

Initial value (˚C)	Final value (˚C)	Flash point observation
30.0	39.0	No Flash
31.0	40.0	No Flash
32.0	44.0	No Flash
37.0	46.0	No Flash
37.0	48.0	Flash Point
37.0	50.0	Flash Point
37.0	52.0	Fire Point
37.0	53.0	Fire Point

From Table 2, it can be observed that the temperature of Jet A-1 was varied while an ignition source was introduced. A flame flashed for some time at 50 ˚C and went out after a very short time of flashpoint. An inference was drawn that 50 ˚C is the flashpoint temperature of Jet A-1. However, from Table 3, the flashpoint temperature was observed to be 48 ˚C, when a flame flashed for a short period and for temperatures above that, it was seen that the flame sustained and erupted into fire. The following inferences were drawn, 48 ˚C is the flashpoint temperature for the second experiment and the fire point is assumed to be any temperature above 48 ˚C. Generally, it was agreed that for this study, the reference flashpoint will be between the range of 48 ˚C to 50 ˚C and the fire point will be temperatures above this range.

2.2. Contaminated jet A-1 samples flash point test

This section focuses on the response of contaminated Jet A-1 to an increase in temperature and the introduction of a fire source for the different volume ratios.

Table 4 is the flashpoint presentation for the ratios of 2:1, 3:1, and 4:1 respectively. By observing the table, the flashpoints of the contaminated samples experienced a significant increase as the volume of Jet A-1 reduces. At a ratio of 2:1, the flashpoint was recorded to be 64 ˚C, which shows that liquid nitrogen has a significant effect on the flashpoint of Jet A-1, which was known before the injection of liquid nitrogen to be between the range of 48 ˚C to 50 ˚C. This appreciable increase in temperature extends the time Jet A-1 becomes flammable. Also, there was an increase in flashpoint temperature for the ratio 3:1 mixture. However, the trend observed for ratios 2:1 and 3:1 was not noticed in ratio 4:1 contaminated Jet A-1 and this is because of the little volume of liquid nitrogen in the mixture. A flashpoint is a minimum temperature at which the vapours of a volatile material ignite if given an ignition source, say Jet A-1. Therefore, increasing the flashpoint of Jet A-1 by such a margin will increase the time it takes for the fuel to ignite, giving an instance of an aircraft crash where the fuel meets an ignition source as compared to its ordinary form.

Table 4. Flashpoint of the contaminated Jet A-1 samples (source: Authors, 2022)

Ratio	Flash Point
2:1	64 ˚C
3:1	56 ˚C
4:1	50 ˚C

The result from the experiment was used to determine how Jet A-1 reacted to the injection of Liquid Nitrogen at different volume ratios in relation to flash point and rate of freezing. The results were drawn and the volume ratio of 2:1 was selected as the most feasible with a noticeable rise in flashpoint to a temperature of 64 ˚C.

This observation was factored in the CFD set-up to help visualize the effects of liquid nitrogen on the temperature of Jet A-1 under heated and normal circumstances. It was noticed that the process drastically reduced its temperature, which in turn led to the rise in the flash point experienced in the experimental set-up.

2.3. Freezing rate and defrosting rate of contaminated jet A-1

Table 5 shows the freezing and unfreezing rates of the volume ratios of contaminated Jet A-1, in which the reaction of Jet A-1 to liquid nitrogen at the different volume ratios was recorded. Also, the freezing and unfreezing times of the samples were taken.

Observing the ratio 2:1 mixture, it was noticed that at about 30 seconds after the addition of liquid nitrogen, Jet A-1 froze, forming a crystalline solid. This observation has shown the possibility of liquid nitrogen in freezing Jet A-1 and contaminating Aviation fuel. The time it took the mixture to unfreeze to its initial temperature of 32 ˚C was recorded to be 17 minutes, and 30 seconds. This information is crucial in understanding the behaviour of Jet A-1 when mixed with liquid nitrogen and how this can help to reduce the flammability of Jet A-1 post-impact. Also, it was also noted that for the volume ratio of 3:1, at 34 ˚C, a crystalline crust was formed only at the top of the mixture while the bottom part of the mixture was jelly-like.

Table 5. Contaminated volume ratio of Jet A-1 (source: Authors, 2022)

Jet A-1	Liquid Nitrogen	Ratio	Observation	Freezing Time	Defreezing Time
40 ml	20 ml	2:1	Mixture Froze	30 sec	17 min, 30 sec
60 ml	20 ml	3:1	The crystalline crust is noticed at the top but dissolves over time.	34 sec	3 min, 10 sec
80 ml	20 ml	4:1	Little crystalline formation in the mixture but dissolved immediately	60 sec	7 sec

This mixture dissolved over time, due to this observation, it was inferred that the quantity of liquid nitrogen to Jet A-1 was not enough to freeze Jet A-1 wholly and because of this, the effect of liquid nitrogen as a contaminant will not be properly exercised. Also in the case of the ratio 4:1 mixture, a small crystalline formation of the mixture ensued but dissolve immediately. From the above observations, the best volume ratio suitable for the adequate freezing of Jet A-1 is 2:1. From the result of the ratio 2:1 mixture, freezing of Jet A1 reduces the ability of the fluid to flow as it should in its normal form due to the crystallization of the fluid.

These phenomena affect the retractability of the fuel in case of an aircraft crash where for instance, there is a puncture in the fuel tank or burst of the fuel tank, it is expected that the fluid will try to flow out of the tank. And if it successfully does that and comes in contact with an ignition source at its flashpoint, it is expected that the fuel will ignite, and start burning, but because the fuel is frozen, it will take a while before it ignites due to the process of transforming from solid to liquid and also, the ability to retrace back to its origin will be relatively low as compared to Jet A-1 in its normal form.

Figure 4 presents the plot of the freezing time rate for the different volume ratios. From the graph, it can be observed that the nucleation time, which is the time it takes before the mixture of Jet A-1 and liquid nitrogen starts to freeze, increases as the volume ratio increase which helps in understanding how much time it will take for the process of contaminating a given ratio of Jet A-1 to start. From the plot of the ratio 2:1 mixture, the nucleation time is 0.075 sec, which is good enough for this study as compared to other ratios. Also, from the plots, it can be observed that for the ratio 2:1 mixture, as the temperature increase, the time increases. This helps to understand that the fluid will continue to freeze regardless of the volume of Jet A-1 and liquid nitrogen in a ratio of 2:1. Figure 5 is plotted in response to Table 5. It reveals that with an increase in volume (20:10, 30:15, 40:20, 80:40…), while preserving the ratio of 2:1, a longer time rate of defreezing is observed.

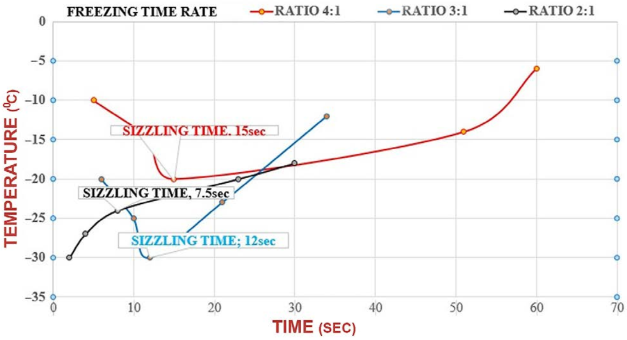

Figure 4. Freezing time rate of Jet A-1 with changes in volume ratio (source: Authors, 2022)

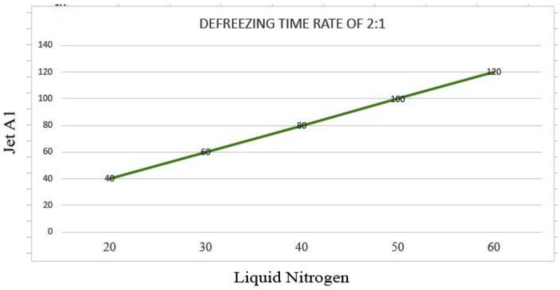

Figure 5. De-freezing time rate of Jet A-1 and liquid nitrogen (2:1) (source: Authors, 2022)

3. Discussion and interpretation of the results obtained

Figure 6a–e displays the temperature contours for the considered multiphase model. It indicates how the temperature decreases as liquid nitrogen flows through the cavity. With increasing time, the contours for the reaction from 1 second to 12 seconds reveal that the temperature distribution reduces as liquid nitrogen continues to flow through the cavity.

At 1 second, Figure 6a reveals a drop in the temperature as liquid nitrogen is being dissipated into the Jet A-1. The topmost part of the cavity is seen to have a temperature that is relatively cold which indicates that the portion of Jet A in that region has been affected by liquid nitrogen. The lower part of the cavity temperature is relatively hotter, this indicates that Jet A in this region is mildly affected by liquid nitrogen.

At 2 seconds, Figure 6b shows a further drop in the temperature as liquid nitrogen is being dissipated into Jet A. The cavity is seen to have a temperature that is relatively cold around 50% of its volume. The lower part of the cavity temperature is still hotter which indicates that Jet A in this region is mildly affected by liquid nitrogen. At 3 seconds, Figure 6c shows a relatively higher drop in the temperature rate as liquid nitrogen is being dissipated into Jet A. The cavity is seen to have a temperature that is relatively cold around 80% of its volume. The lower part of the cavity temperature is still hotter, indicating that Jet A in this region is only slightly affected by liquid nitrogen.

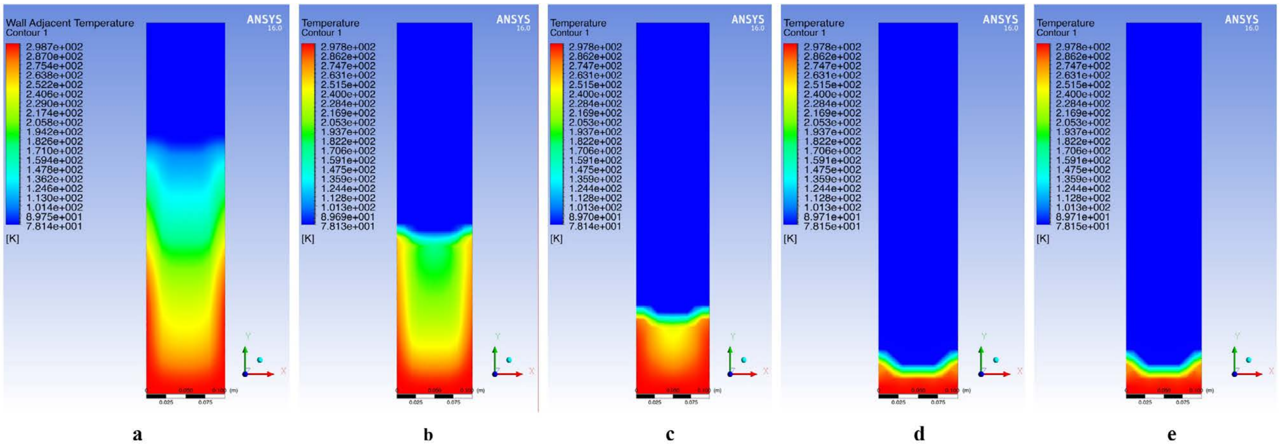

Figure 6. Temperature contour at 1, 2, 3, 7.5 and 12 seconds (source: Authors, 2022)

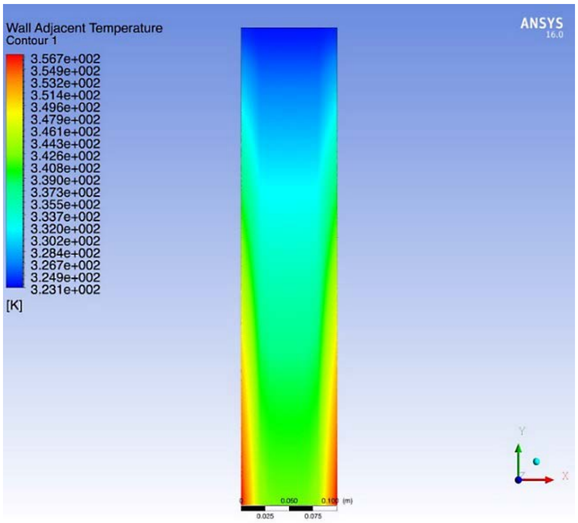

Figure 7. Temperature contour wall containing heated Jet A (source: Authors, 2022)

From 7.5 seconds to 12 seconds, Figures 6d and 6e show the highest drop in the temperature rate within the experimental timeframe of 1 to 12 seconds. The cavity was observed to have a temperature that is relatively cold around 90% of its volume.

Figure 7 describes the temperature distribution of Jet A only when the wall of the cavity is heated by 1000 ˚C. It can be observed that temperature increased drastically in regions close to the wall. This is physically seen when the Aircraft and its structures are on fire. Levels of this heat and above are what is experienced during a post-impact crash.

Conclusions

The impact of injecting liquid nitrogen into aviation fuel has been extensively investigated and enables us to realize that at a 2:1 mixing ratio of Jet A-1 and liquid nitrogen, a significant increase in the flashpoint temperature from an average of 48 ˚C to 64 ˚C. This shows the mixing ratio of 2:1 as the best considering it stalls the combustion of Jet A1 fuel long enough for passenger evacuation. This, when scaled up in the field of civil aviation safety, is a huge win.

Considering the freezing time, the 2:1 mixing ratio of Jet A-1 and liquid nitrogen took 30 seconds for the to freeze. In the event of an unavoidable crash, this time is considered short enough for infusing liquid nitrogen into aviation fuel before impact.

The experiment also shows that the 2:1 mixing ratio of Jet A-1 and liquid nitrogen took 17 minutes and 30 seconds to return to its original liquid state which would be substantial enough when considering the time needed to evacuate stranded passengers from the crash site.

The other considered mixing ratios showed potential in increasing the flash point of Jet A-1 but failed to retain their frozen state for long periods, which makes them less effective in curbing the issue of post-impact fire.

Recommendations

A flash point test setup was developed in the absence of a proper test set up which included a heater, a thermometer, a stopwatch, and beakers. Also, a tin container was utilized in carrying out the contamination experiment as it not only aids easy detection of temperature changes using a thermometer but also makes the effect of liquid nitrogen on Jet A-1 to be easily noticed. A more sophisticated setup is recommended for larger volumes of specimens.

Liquid Nitrogen Injection into Aviation Fuel to reduce its flammability and post-impact fire has the potential to save lives. In view of these, the fit is recommended that the most preferred ratio to mitigate the flammability rate is 2:1 as specified above. With this ratio, there was a dramatic increase in the flashpoint, to 64 ˚C, thus aiding safety in cases of post-impact fire.

Since this research does not focus on the design aspect, it is suggested that an implementation of a liquid nitrogen cryogenic pipe system over the fuel tank with pores, through which the liquid nitrogen is injected to contaminate the Jet A-1.

Acknowledgements

This research was supported by Kwara State University, Malete. Mr. Rasheed Abiodun Jimoh was helpful as a laboratory assistant throughout the timeline of the research.

Funding

This paper was self-funded by the corresponding Author.

Author contributions

Abdulbaqi Jinadu conceived the idea in October 2019 after the Boeing 737 MAX (Lion Airflight 610) crashed. He was also responsible for setting up the research team and laying out guidelines to oversee the research. Olalekan Adebayo Olayemi and Ayodeji Tunde Akangbe were responsible for data collection and analysis. Abdul-Haleem Olatinwo, Tiniakov Dmytro, and Volodymyr Koloskov were responsible for the data interpretation and scrutinization of the manuscript.

Disclosure statement

The authors declare that they have no conflict of interest.

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Notations

Variables and functions

$\{Dt/Du\}$ – Substantial time derivative of velocity;
F – External body forces;
f_x – External force;
g – Acceleration due to gravity;
I – Unit tensor;
J_j – Diffusion flux;
k_{eff} – Effective conductivity;
Re – Reynolds Number;
S_m – Source term;
T – Thrust;
u – Velocity vector in x direction;
V – Velocity vector;
μ – Viscosity;
ρ – Density;

ρ_u, ρ_v – Rate of mass entering in x, y direction respectively;
ρV – Mass flux;
τ – Shear stress;
τ – Stress tensor;
$\partial/\partial t$ – Rate of change in time;
∇ – Vector operator;
$\nabla.(\rho V)$ – Divergence of ρV.

Abbreviations
AMK – Anti-Misting Kerosene;
CFD – Computational Fluid Dynamics.