

Analytical investigation into the effects of nitrogen enriched air bubbles to improve aircraft fuel system water management

Yuri Terada

School of Aerospace, Transport
and Manufacturing,
Cranfield University,
UK
y.terada@cranfield.ac.uk

Craig P Lawson

School of Aerospace, Transport
and Manufacturing,
Cranfield University,
UK
c.p.lawson@cranfield.ac.uk

Amir Z Shahneh

School of Aerospace, Transport
and Manufacturing,
Cranfield University,
UK
a.zareshahneh@cranfield.ac.uk

ABSTRACT

In the aircraft fuel system, water/ice contamination within fuel tanks has been one of the most serious challenges. This issue was highlighted in 2008 by an accident triggered by restricted fuel flow due to the ice formation within the system. The On Board Inert Gas Generation System (OBIGGS), which is already installed on some aircraft to prevent the outbreak of fire in the fuel tank, is a potentially feasible method to improve the water management. This paper focuses on the impact of bubbles from the OBIGGS system on water in the fuel tank.

In order to explore the bubble effect, the relationship between orifice configuration and bubble parameter was investigated by means of mathematical models and existing experimental data. Moreover, by combining a MATLAB code and the introduced bubble model, the effect of bubble size and rising speed on the water contamination in the fuel tank was observed. For the water absorption process, a new model was introduced using a mass transfer coefficient. Finally, this article concludes that the amount of accumulated water is dependent on the bubble size and rising speed, and an optimal bubble size or speed is predictable once the coefficient has been obtained.

KEYWORDS

Aerospace, aircraft, water contamination, fuel system, On Board Inert Gas Generation System, Nitrogen Enriched Air, bubble

NOMENCLATURE

A_b	Interfacial area between fuel and a bubble, m ²
Bo	Bond number, -
d_m	Bubble diameter, m
d_o	Orifice diameter, m
Fr	Froude number, -
g	Gravitational acceleration, 9.81 m/s ²
Ga	Galileo number, -
H	Height, m
K	Mass transfer coefficient, mol/(Ns)
M	Molar mass, kg/mol
N_b	Number of bubbles injected into the fuel per second, /s
$N_{orifice}$	Number of orifice, -
n	Amount of substance, mol
$\dot{n}_{H_2O}$	Amount of substance from fuel to a bubble per unit time, mol/s
p	Pressure, Pa
Δp_{H_2O}	Water pressure difference between fuel and injected Nitrogen Enriched Air bubbles, Pa
Q	Gas flow rate, m ³ /s
R_0	Universal/Molar gas constant, 8.314 J/(mol K)
r_o	Orifice radius, m
Re	Reynolds number, -
ρ	Density, kg/m ³
S	Water solubility, %
σ	Surface tension, N/m
t	Time, s

T	Temperature, K
μ	Dynamic (Absolute) viscosity, Ns/m ²
ν	Kinematic viscosity, m ² /s
U_T	Bubble rising speed, m/s
U_{SO}	Superficial gas speed, m/s
V_b	Volume of a bubble, m ³
V_{NEA}	Nitrogen Enriched Air gas flow rate, m ³ /s
We	Weber number, -

INTRODUCTION

The phenomenon of water in aviation fuel is well documented¹ and results in regular maintenance action. In July 1996, the accident of Trans World Airlines, Boeing 747-13, was associated with an ignition of flammable air and fuel mixture in the centre wing fuel tank (CWT), resulting in the explosion of the tank.² In addition to this, the CWT is located within the fuselage, and fuel or fuel vapour are kept warm by heat output from the cabin and systems, while the wing fuel tanks are cooled down because of the exposure to the low ambient temperature during cruise. Furthermore, the positions of environmental control system equipment are often near to the CWT and out heat causing transfer to the fuel. This contributes to the increase of the volatility of fuel and possibility of ignition.³

Considering the accident and hazard assessment, CS 25.981 sets the requirement for aircraft to minimise the flammability of the fuel vapour and to avoid catastrophic failure due to ignition of fuel or gas.⁴ For over ten years, OBIGGS, which generates and injects inert gas into the fuel tank, has been developed to help aircraft satisfy the regulation. OBIGGS started to be installed on civil aircraft such as the Airbus 350 XWB or Boeing 787, using the benefits of dry warm Nitrogen Enriched Air (NEA).

OBIGGS is also deemed as a potentially good solution to water/ice contamination of fuel.^{5,6} In January 2008, British Airways, Boeing 777-236ER aircraft crashed at London Heathrow Airport because of an unexpected reduction in thrust. According to the final report, the Air Accidents Investigation Branch concluded that the incident was caused by restricted fuel flow triggered by the ice formation within the fuel system and the ice concentration at a fuel oil heat exchanger.⁷ As previously mentioned, the initial purpose of OBIGGS was to avoid the mixture of flammable fuel and air which could ignite in the tank. This is enabled by expelling air from the tank and keeping the amount of oxygen within a limited value. In terms of the water contamination, the water is generated by the two sources: precipitation of dissolved water and condensation of moist air.⁵ The OBIGGS can reduce humidity in the tank and warm the ullage or fuel to prevent water contamination. Therefore, OBIGGS could save the time and the cost of maintenance by stopping the water contamination as shown in Figure 1.

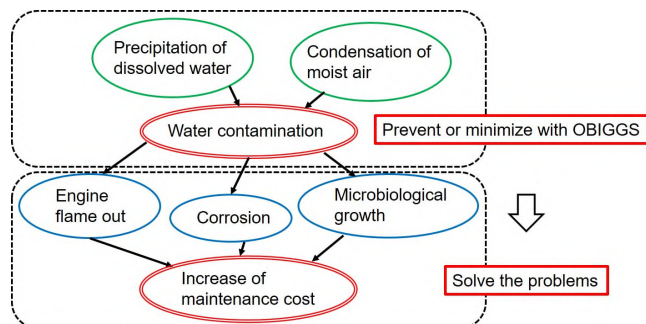


Figure 1. Causes and results of water contamination.

APPLICATION OF OBIGGS TO WATER MANAGEMENT

Taking account of the source of water contamination within aircraft fuel tanks, OBIGGS has been spotlighted as an innovative solution for the problem. This is because the system of OBIGGS is relatively simple with few moving parts, hence a light-weight, low-cost, and reliable system can be achieved. According to Federal Aviation Administration (FAA) report, the system for the B747 will be 160 pound (72 kg) and \$150,000 - \$200,000.⁸

Concerning the feature of the OBIGGS system, the following points help the fuel tank to prevent the water contamination in flight:

- 1) Fuel or ullage warming: NEA gas is usually pre-warmed for the efficiency of the Air Separation Module (ASM). Therefore, the injected NEA gas has a higher temperature compared to the tank. It can be expected to increase the fuel or ullage temperature and help to reduce the amount of precipitated or condensed water. However, because the mass and specific heat capacity of the NEA gas is much smaller than those of the fuel, the effect of this warming might be insignificant.
- 2) Humid air expulsion from the ullage: The directly injected NEA gas into the ullage has low humidity. Therefore, the dry air can expel the humid air from the ullage through the vent system.
- 3) When the dry NEA gas is injected into the fuel, dehydration occurs because of the pressure and humidity differences. This phenomenon reduces the precipitation of water in the fuel.

When the NEA is injected into the fuel, the diameter of the bubbles determines their shape and velocity, and as a result, it affects their residence time in the fuel. In other words, the rate of water transfer to the bubble depends on the bubble size, hence it affects the amount of the accumulated water. This research aims to calculate the amount of dissolved or precipitated water in the fuel by taking account of bubbles parameters. By revealing the effect of the bubbles, it may become possible to control them and generate desirably-sized ones from NEA injection. Alternatively, the number of bubbles in the fuel can be maintained to optimise the quantity of water absorbed by the bubbles. These approaches may improve the efficiency of the system.

FUEL TANK AND OBIGGS MODEL

The existing fuel tank and OBIGGS model has been developed over several years at Cranfield University. Work has generally focused on improving a CWT of A320.⁹ In the model, the flight profile is assumed to have three constant phases: climb, cruise and descent. The parameters of the fuel tank and OBIGGS used in this simulation will be precisely described in the “simulation and result” section. The temperatures of the fuel and the ullage are calculated by heat transfer between the outside and the inside of the CWT.¹⁰ Concerning the major causes of water contamination, the following phenomena are considered:¹¹

- Inflow/Outflow through the vent system
- NEA gas injection, absorption of dissolved water
- Water condensation on the wall
- Water precipitation in the fuel

Regarding the second point, the injected NEA gas is assumed to absorb the dissolved water perfectly up to its saturation point regardless of how long it remains in the fuel. Therefore, the following sections of this paper discuss more precisely the effect of the NEA bubbles on the water absorption.

BUBBLE MODEL

Bubble diameter

In this section, a review of previous studies about bubble size or rising velocity injected from a probe into liquids is carried out, followed by a validation of suggested mathematical formulas using existing experimental data. Finally, the method is applied to the current fuel tank model.

Bubble size is one of the key parameters and clarifying it is a challenge to determine two-phase gas-liquid phenomena. Although a lot of experiments or theoretical analysis have been conducted over the past decades, one clear single method has not been established as of today. However, summing up these studies, it can be widely recognized that the bubble size depends on the following six parameters:

- Orifice diameter d_o [m]
- Gas flow rate Q [m³/s]
- Liquid density ρ_L [kg/m³]
- Surface tension σ [N/m]
- Dynamic viscosity μ [Ns/m²]
- Gravitational acceleration g [m/s²].

Since, in total three physical variables are used in these six parameters, bubble diameter can be expressed with three dimensionless numbers according to Buckingham Π theorem:

$$f(\Pi_1, \Pi_2, \Pi_3) = 0 \quad (1)$$

Akita and Yoshida¹² developed a mathematical model satisfying the condition:

$$\frac{d_m}{d_o} = 26 \left(\frac{d_o^2 g \rho_L}{\sigma} \right)^{-0.5} \left(\frac{d_o^3 g}{\nu^2} \right)^{-0.12} \left(\frac{U_r}{\sqrt{g d_o}} \right)^{-0.12} \quad (2)$$

This equation was obtained by dimensional analysis and had been widely used for over 40 years. Jamialahmadi et al.¹³ improved this model based on neural network analysis and confirmed that the new method could predict the bubble diameter for various surface tensions or liquid viscosities. The correlation was obtained as follows:

$$\frac{d_m}{d_o} = \left[\frac{5.0}{Bd_o^{1.08}} + \frac{9.261 Fr^{0.36}}{Ga^{0.39}} + 2.147 Fr^{0.51} \right]^{\frac{1}{3}} \quad (3)$$

where Bd_o , Fr , and Ga represent the Bond number, Froude number, and Galileo number respectively and can be written as follows:

$$Bd_o = \frac{d_o^2 g \rho_L}{\sigma} \quad (4)$$

$$Fr = \frac{U_{so}^2}{g d_o} \quad (5)$$

$$Ga = \frac{d_o^3 g}{\nu^2} \quad (6)$$

where U_{so} is the initial speed at the injection nozzle (see Figure 2) determined by dividing the injected gas flow Q by the orifice area πr_o^2 :

$$U_{so} = \frac{Q}{\pi r_o^2} \quad (7)$$

In this study, it can be alternatively written as follows:

$$U_{so} = \frac{V_{NEA}}{N_{orifice} \cdot \pi \left(\frac{d_o}{2} \right)^2} \quad (8)$$

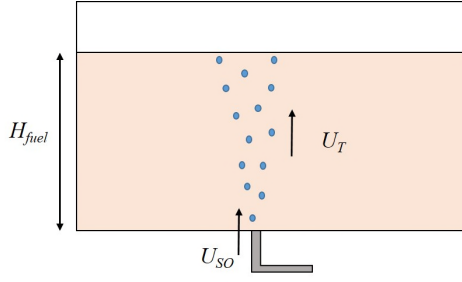


Figure 2. Bubble model.

To verify this method, a comparison with independent experimental research results conducted by Ramakrishnan et al.¹⁴ was performed in this research. In the experiment, three different types of glycerol which have various dynamic viscosities were investigated with orifice diameter $d_o = 3.7$ mm. NEA bubbles formed at the orifice mounted on the bottom of the liquid column rose to the ullage of the cylinder. Table 1 shows the properties¹⁵ and the values calculated by employing equations (3) to (8). In Table 1, the content rate indicates the concentration of the glycerol in a water solution. Because the Froude number is calculated by the gas flow rate at each data point, the other two numbers; Galileo and Bond, are shown in the table.

Table 1.
Properties of glycerol for comparison.¹⁵

			Dynamic viscosity μ [cP]		
			45	302	552
Content rate	W	[%]	76.9	91.8	95.3
Surface tension	σ	[N/m]	0.066	0.064	0.064
Density	ρ	[kg/m ³]	1200	1240	1248
Kinematic viscosity	ν	[m ² /s]	3.7×10^{-5}	2.4×10^{-4}	4.4×10^{-4}
Galileo number	Ga	[-]	3.6×10	8.6	2.6
Bond number	Bd_o	[-]	2.4	2.6	2.6

* 1 cP = 10 P = 0.001 Ns/m²

Figure 3 shows the result of the comparison. The points illustrate the experimental values given by Ramakrishnan et al.¹³, and the curves represent equation (3). Although the case for $\mu = 302$ cP does not match the experiment result, the other two cases seem to have good agreement with the data.

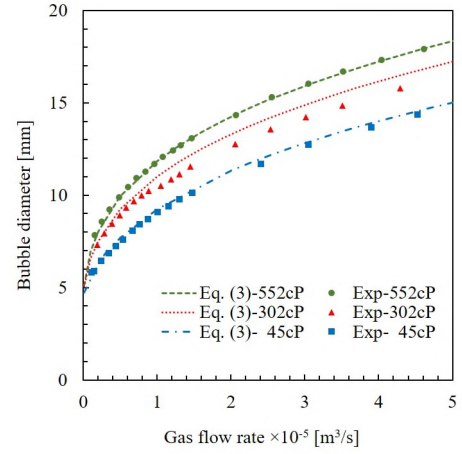


Figure 3. Comparison the mathematical equation with an experimental data.

The errors between the values of equation (3) and the ones of experiment are presented in Table 2. Even for the liquid of $\mu = 302$ cP, the maximum relative error is 6.0% at $Q = 1.1 \times 10^{-5}$ m³/s. Considering the experiment itself includes some errors, it is reasonable to judge that the equation (3) is valid for calculating the bubble diameter based on the liquid properties, orifice size, and gas flow rate.

Table 2.
Percentage errors for comparison.

Error [%]	Dynamic viscosity μ [cP]		
	45	302	552
Maximum	2.9	6.0	2.7
Mean	1.8	4.0	0.5

In order to evaluate the possible error in the calculation using Jet A-1 properties, another comparison using different liquid data provided by Kulkarni et al.¹⁶ was conducted as illustrated in Figure 4. This data was chosen because the liquid properties were close to the ones of Jet A-1. The values are shown in Table 3. The orifice diameter was set as $d_o = 2.5$ mm to be consistent to the experimental condition.¹⁵

Table 3.
Properties of liquids.¹⁷

			Water	Propanol
Surface tension	σ	[N/m]	0.073	0.0238
Density	ρ	[kg/ m ³]	1000	803.7
Kinematic viscosity	ν	[m ² /s]	1.0×10^{-6}	2.9×10^{-6}

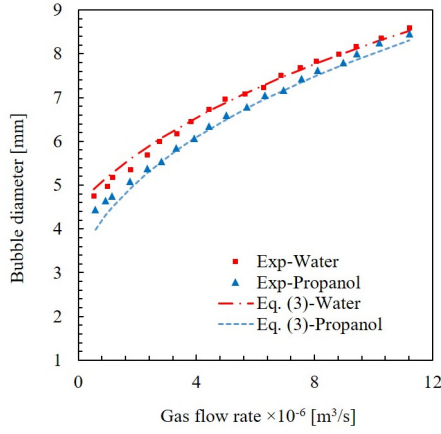


Figure 4. Comparison using different liquids.

The mean percentage error (MPE) values for water or propanol condition were calculated as 1.4% and 2.4% respectively. Each MPE was calculated using the following equation:

$$\text{MPE}[\%] = \frac{100}{n} \sum_{i=1}^n \frac{X - x_i}{X} \quad (9)$$

where x and X represent the experimental data and the theoretical value at each gas flow rate respectively. n indicates the number of data points.

It should be noted that the NEA gas flow rate, in this case, is one order smaller than the one in Figure 3. However, the equation still has a positive match with the experiment result. Considering that the value of fuel properties exists between the ones of water and propanol, the MPE was also selected at the point which internally divides the two MPE values and resulted in 2.3%.

Rising speed

Regarding the bubble rising velocity, Zheng et al.¹⁸ presented a new method which categorises the bubble size and adapted different rising velocity formulas respectively. The feature of the formulas is that the equations compensate the errors caused by assuming that the bubbles are spherical while in reality their shape is ellipsoidal.

1) Small size ($d_m \leq 1\text{mm}$)

$$U_r = \frac{\text{Re} \mu}{\rho_L d_m} \quad (10)$$

here the Reynolds number Re can refer to the following equations:

$$\text{Re} = \frac{N_D}{24} - 1.7569 \times 10^{-4} N_D^2 + 6.9252 \times 10^{-7} N_D^3 - 2.3027 \times 10^{-10} N_D^4 \quad (11)$$

when $N_D \leq 73^*$,

$$\text{Re} = 10^{-1.7095 + 1.33438W - 0.11591W^2} \quad (12)$$

when $73 < N_D \leq 580$,

$$\text{Re} = 10^{-1.81391 + 1.34671W - 0.12427W^2 + 0.006344W^3} \quad (13)$$

when $580 < N_D \leq 1.55 \times 10^7$.

$$^* N_D = 4\rho_L(\rho_L - \rho_G)gd_m^3 / 3\mu^2$$

$$^{**} W = \log N_D$$

2) Intermediate size ($1\text{mm} < d_m \leq 15\text{mm}$)

$$U_r = \frac{\mu}{\rho_L d_m} M^{-0.149} (J - 0.857) \quad (14)$$

where M and J are functions of liquid and NEA gas properties:

$$J = 0.94H^{0.757}, \quad (2 < H \leq 59.3)$$

$$J = 3.42H^{0.441}, \quad (59.3 < H)$$

$$H = \frac{4}{3} E_o M^{-0.149} \left(\frac{\mu}{\mu_w} \right)^{-0.14} \quad (15)$$

in which μ_w is the dynamic viscosity of water, and E_o and M are

$$M = g\mu^4 \frac{(\rho_L - \rho_G)}{\rho_L^2 \sigma^3}$$

$$E_o = g \frac{(\rho_L - \rho_G)d_m^2}{\sigma} \quad (16)$$

3) Large size ($15\text{mm} < d_m$)

$$U_r = 0.711 \sqrt{\frac{g(\rho_L - \rho_G)d_m}{\rho_L}} \quad (17)$$

Note that the suffixes for the density: L and G , represent liquid and gas respectively, and d_m indicates equivalent bubble diameter for ellipsoidal shape bubbles. Zheng et al. have already verified this method by the comparison with experimental data using 90.6% glycerol.¹⁸

Figure 5 represents the relationship between the size of a bubble and its velocity in Jet A-1 based on the above formulae. It can be found that when the bubble diameter is between 3.5 and 15 mm, its movement speed in immobile fuel is approximately 0.2 m/s. Table 4 shows the properties of Jet A-1 for the calculation at 15 °C.¹⁹

Table 4.
Properties of Jet A-1 at 15 °C.¹⁹

		Values
Surface tension	σ	0.0238 [N/m]
Density	ρ	803 [kg/m³]
Kinematic viscosity	ν	1.8×10^{-6} [m²/s]

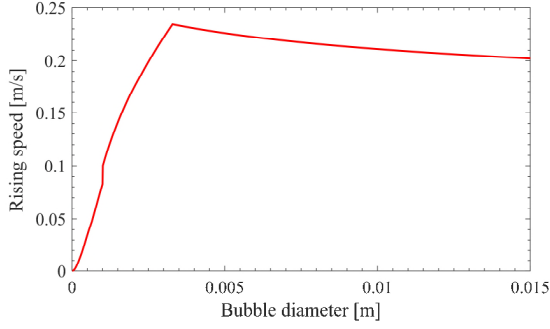


Figure 5. Relationship between bubble diameter and its speed in Jet A-1 fuel at rest.

Water transfer

In general, mass transfer in two-phase flow can be expressed in a time derivative form. In this research, because the water pressure difference between a bubble and fuel can be obtained for each time step and for the simplification, following equation was introduced to express the amount of substance of water from fuel to a bubble per unit time [mol/s]:

$$\dot{n}_{H_2O} = K A_b \Delta p_{H_2O} \quad (18)$$

where, A_b is the surface area of an injected NEA bubble, and Δp_{H_2O} is the water pressure difference between the fuel and the bubble, which is expressed as

$$\Delta p_{H_2O} = \begin{cases} p_{H_2O}^{fuel} - p_{H_2O}^{NEA}, & \text{for } p_{H_2O}^{fuel} < p_{H_2O}^{sat} \\ p_{H_2O}^{sat} - p_{H_2O}^{NEA}, & \text{for } p_{H_2O}^{fuel} \geq p_{H_2O}^{sat} \end{cases} \quad (19)$$

Equation (19) indicates that the pressure difference depends on the water partial pressure $p_{H_2O}^{fuel}$ in the fuel or saturated water pressure in the bubble $p_{H_2O}^{sat}$. In this simulation, the partial pressure of water in the NEA gas $p_{H_2O}^{NEA}$ is given as one of the parameters of the system, which is 13 Pa.²⁰

The coefficient K represents the easiness of the mass transfer, and concerning the unit consistency, the unit can be expressed as mol/(Ns). The value of the coefficient should vary with the type of liquid and gas. However, it is not easy to find the exact value for an oil-air-water system. Hence, through several iterations, some possible values were decided in the simulation, and the effectiveness of the value K was investigated.

By taking account of the residence time of a bubble, the amount of water which one bubble can absorb from its generation until the explosion can be written as follows (refer to Figure 2):

$$n_{H_2O}^{absorb} = \dot{n}_{H_2O} \Delta t = \dot{n}_{H_2O} \frac{H_{fuel}}{U_T} \quad (20)$$

where Δt is the time for the bubbles to rise from the tip of the orifice to the boundary with ullage. Note that this is assuming the rising speed U_T is constant and is the terminal speed calculated by equations (10) to (17).

Water precipitation

The number of bubbles generated by the NEA gas per second is obtained by

$$N_b = \frac{V_{NEA}}{V_b} \quad (21)$$

Concerning equations (18) and (20), the amount of dissolved water per mole at time i can be expressed as follows:

$$n_{H_2O}^{fuel}(i) = n_{H_2O}^{fuel}(i-1) - N_b \cdot n_{H_2O}^{absorb} \quad (22)$$

It is common knowledge that the water solubility depends on the fuel temperature. The dissolved water itself does not contribute to the water contamination or concomitant serious accidents.²¹ However, once the dissolved water comes out of solution as free water or is collected as a puddle at the bottom of the tank under the low-temperature condition, it could lead to operating issues associated with the water. Since it is not easy to remove the dissolved water by a mechanical process such as filtration, other methods are necessary to avoid the water contamination.

Water solubility of aviation fuel has an exponential relationship with the fuel temperature:

$$S = s_0 \exp(s_1 T_{fuel}) \quad (23)$$

where s_0 is the base coefficient which matches the water solubility in the fuel at 0 °C, s_1 is a slope of the log relationship between the temperature and the solubility, and T_{fuel} is the fuel temperature in °C. In this research, based upon an aviation fuel property handbook,¹⁹ the following values are cited: $s_0 = 27 \times 10^{-4}$ % v/v, $s_1 = 0.030$ °C⁻¹ for Jet A-1.

Using the water solubility of the fuel, S , the amount of substance of dissolved water at saturation can be

$$n_{H_2O}^{fuel, sat} = \frac{S \rho_{H_2O} V_{fuel}}{M_{H_2O}} \quad (24)$$

Therefore, equations (23) and (24) give the amount of the precipitated water⁶:

$$n_{H_2O}^{fuel, pre} = \max\{n_{H_2O}^{fuel}(i) - n_{H_2O}^{fuel, sat}, 0\} \quad (25)$$

Water condensation

When moist air flows from outside the tank through the vent system, or NEA bubbles release vapour into the ullage, water condensation tends to occur on cold surfaces such as the tank walls or vent pipes.

On the assumption that all the water-absorbed bubbles explode at the surface and release the water into the ullage, the partial pressure in the ullage can be expressed as follows:

$$p_{H_2O}^{ullage(i)} = p_{H_2O}^{ullage(i-1)} + N_b \cdot \frac{n_{H_2O}^{bubble} R_0 T_{ullage}}{V_{ullage}} \quad (26)$$

Using the Rankine's equation, the saturation pressure of the ullage p_{sat}^{ullage} can be calculated as²²

$$p_{sat}^{ullage} = 101325 \exp\left(13.7 - \frac{5120}{T_{ullage}}\right) \quad (27)$$

Hence, the partial pressure of condensed water in the ullage is

$$p_{H_2O}^{condens} = p_{H_2O}^{ullage} - p_{sat}^{ullage} \quad (28)$$

If the relative humidity is greater than 1 (supersaturation), the amount of condensed water in the ullage is

$$n_{H_2O}^{condens} = \frac{p_{H_2O}^{condens} V_{ullage}}{R_0 T_{ullage}} \quad (29)$$

SIMULATION AND RESULT

Simulation using condition of A320 flight experiment

For the calculation of the amount of the water accumulation, the flight data of A320 given by FAA²³ was used. The CWT with 8.2 m³ capacity was assumed as a simple rectangular box without any partitions referring to the report.²³ Table 5 shows the simplified geometry of the tank. The initial fuel load is 1500 kg which is equal to 23% of the tank volume, and fuel consumption rate was set to zero according to FAA experiment condition. For the simulation, the following environmental features were considered: atmospheric properties, NEA gas inflow, fuel and ullage temperature (heat transfer) and gas composition. The dissolved water and the temperature were assumed as uniformly distributed in the fuel. The FAA experiment data shown in Figure 6 indicates two different NEA gas flow rate modes. The high-flow mode during the descent phase supplies more NEA to avoid the humid air of the atmosphere entering the tank through the vent system.

Table 5.
A320 CWT geometry.

	[m]
Length (Side surfaces)	2.74
Width (Front and rear surfaces)	3.35
Height (Maximum)	0.91

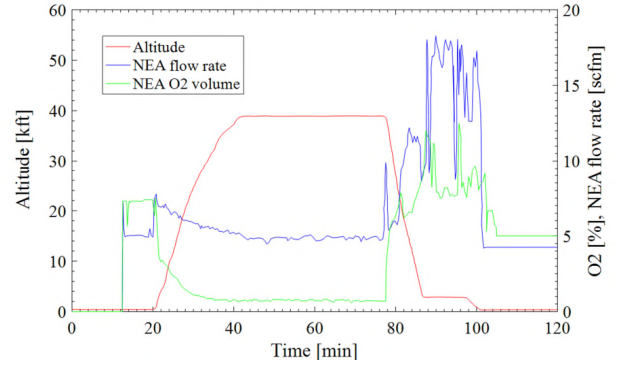


Figure 6. A320 flight test profile from FAA.²²

Partial validation of the code

The main part of the simulation code which calculates the ullage properties, especially for condensation calculations, was validated by comparing the oxygen concentration in the ullage with the FAA result in the zero fuel case. In Figure 7, it can be confirmed that the simulation result has close agreement with the experimental data especially for the cruise phase; in addition, the mathematical model used in the simulation follows the real phenomena. It should be noted that validation was conducted only with the ullage data due to the lack of the experimental data source. However, because this simulation includes heat transfer between the ullage and the fuel, and the temperatures affect the oxygen content in the ullage, at least it can be said that the fuel temperature roughly matches the one of FAA experiment.

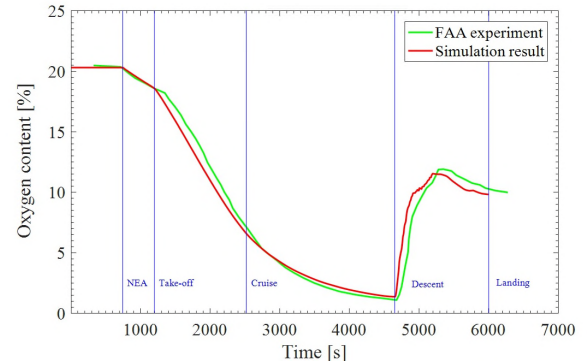


Figure 7. Comparison of ullage oxygen concentration between FAA experiment and simulation result.

Result of bubble effect

The bubble diameter and velocity were obtained in the simulation under the conditions set to match the FAA experiment. Following the conditions of the FAA experiment such as altitude or NEA gas flow rate, several combinations of the orifice diameter d_o and the number of orifices $N_{orifice}$ determined the bubble parameters: bubble diameter d_m , bubble rising speed U_r , and superficial gas speed U_{SO} .

The orifice diameter d_o was changed from 2 mm to 10 mm, and the number of orifices $N_{orifice}$ was varied from 100 to 1000.

The superficial velocity U_{SO} is usually equivalent to the injection velocity at the nozzle. Even though some penalty may be caused due to the efficiency and the practical injection speed may be less than the superficial velocity, the magnitude should be similar to the rising speed. Impractical values such as over 10 m/s should not be used in this simulation because the phenomena could bring about inaccuracy. Figure 8 illustrates the result over a 120-minute period as an example, under the condition of $d_o = 5$ mm and $N_{orifice} = 500$, which has similar values for the injection and rising velocity.

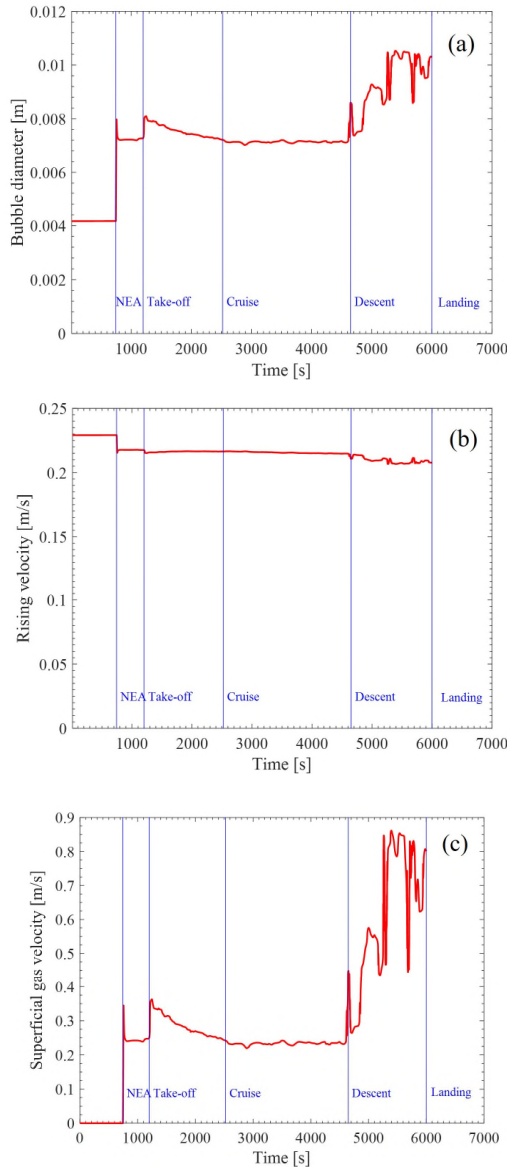


Figure 8. Bubble parameter change in flight: (a) bubble diameter, (b) rising velocity, (c) superficial gas velocity.

Secondly, the relationship between the bubble diameter and the accumulated water was investigated.

As previously mentioned, the gas flow rate depends on the flight mode. Additionally, parameters such as diameter and velocity vary with the time because their parameters are affected by the environmental differences such as liquid density due to the temperature change. Therefore, to make the comparison easy, the average values during the stable cruise phase $t = 2500 - 4500$ s were analysed.

The mass transfer coefficient K was obtained through several iterations. In the calculation, the accumulated water is a sum of precipitated water and condensed water, and the balance depends on how much the bubbles transfer the dissolved water to the ullage. Since there were no information available about the value for oil-air-water problem, the simulation was repeated, and it was found that when K is around 5×10^{-7} mol/(Ns), the total accumulated water has less enough values compared to the non-inerted case.

Figure 9 shows the amount of accumulated water for various mass transfer coefficients: $K = 4 \times 10^{-7}$, 5×10^{-7} , 6×10^{-7} mol/(Ns). Each bubble diameter and velocity was determined for different orifice configurations.

In the figure, an optimal bubble diameter (a) and rising speed (b) to minimise the contamination can be detected in each curve. Moreover, it can be found that in the regime of precipitation, the smaller bubble or bigger rising velocity tends to inhibit the water contamination.

In the mathematical model, the total water mass transfer is expressed as follows:

$$m_{H_2O}^{absorb} = N_b \cdot n_{H_2O}^{absorb} \cdot M_{H_2O} = \frac{6V_{NEA}}{d_m} \cdot K \Delta p_{H_2O} \cdot \frac{H_{fuel}}{U_T} \cdot M_{H_2O} \quad (30)$$

In equation (30), the absorbed water is inversely proportional to the bubble size and rising velocity. However, the result of Figure 9 (b) does not follow this analytical model. This is presumably due to the relationship between bubble size and its rising speed as shown in Figure 5, and the influence of bubble size on water contamination is more dominant than that of bubble speed.

Finally, from this result, it can be said that once the mass transfer coefficient K is deduced, the optimal point can be predicted in terms of the water contamination. Consequently, the number and diameter of the orifice can be calculated to obtain the desirable values of diameter and rising speed of the bubble.

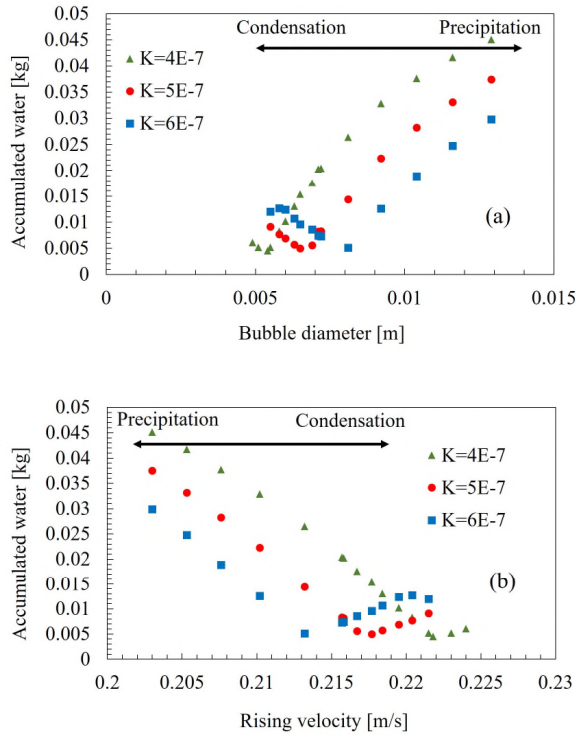


Figure 9. Effect of bubble diameter and rising speed on water contamination: (a) accumulation and bubble diameter, (b) accumulation and bubble rising speed.

CONCLUSIONS

The main objective of this research was to propose a new model for application in using OBIGGS for water management in aircraft fuel. Although many studies about bubble size and speed determination exist, an innovative analytical modelling of the bubble applied to the aircraft fuel system was introduced from previous studies. The selection of the models was conducted based on the good agreement in the comparison with existing experimental data, using a liquid which has similar properties to Jet A-1.

Several orifices with various numbers and diameters were investigated related to the bubble size and the speed. It was found that the number of the orifices or its diameter dominated the bubble size, but the magnitude of the rising speed difference was only 0.01 m/s.

Concerning the bubble parameters, it is widely known that the number of different-sized bubbles in a column follows the gamma or log-normal distribution. In this research, the average diameter based on the gas flow rate information was used for the calculation. Therefore, future work might investigate more precise bubble size distribution and its velocity using several types of orifice.

By combining the bubble model and a MATLAB simulation code based on the FAA experiment, the effect of the presence of bubbles on the water contamination was studied. The mass transfer coefficient was introduced and its value was determined by repeating the simulation and

finding the reasonable range: $K \approx 5 \times 10^{-7} \text{ mol/(Ns)}$. In this range, the total amount of accumulated water is less compared to the one of non-inerted case, and also includes minimum points between the condensation and precipitation regimes. It should be noted that this paper suggests that optimum point depends on the coefficient K . In order to verify this value range, additional experiments are necessary.

It has been previously reported that gas-liquid mass transfer can be accelerated by increasing the residence time of bubbles or increasing the interfacial area.²⁴ However, the simulation result shows that the long residence time does not necessarily accelerate the dehydration of dissolved water. This is because, although the amount of water which is transferred from the fuel to the bubble is inversely proportional to the rising speed U_T , the speed itself is also related to the bubble scale, and the staying time has less impact on the water accumulation compared to the bubble diameter.

Furthermore, for the amount of accumulated water, the optimal point exists in terms of the bubble size and the terminal velocity. From the above results, the orifice properties can be designed to attain ideal bubbles.

If the best orifice configuration cannot be achieved due to space or weight limitations, either precipitation or condensation can be dominant, and it depends on the size of bubble or speed from the optimal point. In the precipitation regime, a greater mass transfer coefficient is more effective because more water can be absorbed. On the other hand, in the condensation area, the bigger mass transfer coefficient accelerates the contamination. However, if any mechanism, such as a membrane, to retain the condensed water on the wall is available, the effect of water condensation can be decreased. This proves that the optimal point is expanded toward the condensation regime, and more varied options can be used for the orifice properties.

REFERENCES

1. Baena S, Repetto SL, Lawson CP, Lam JK-W. Behaviour of water in jet fuel - A literature review, *Progress in Aerospace Sciences* 2013; 60: 35-44.
2. National Transportation Safety Board. Aircraft accident report, In-flight breakup over the Atlantic Ocean, Trans World Airlines Flight 800, Boeing 747-131. Report, Washington, DC, August 2000.
3. Langton R, Clark C, Hewitt M and Richards L. *Aircraft fuel systems*. Chichester, UK: John Wiley & Sons, 2009.
4. European Aviation Safety Agency. Certification specifications and acceptable means of compliance for large aeroplanes CS-25 / Amendment 17. July 2015.
5. Lawson CP and Lim KM. The state-of-the-art and the future of water management within fuel tanks. In: *26th ICAS congress*, Alaska, USA, 14-19 September 2008.
6. Wetterwald M, Lawson CP and Lam JK-W.

- Feasibility study of OBIGGS for water contamination control in aircraft fuel tanks. In: *10th AIAA ATIO conference*, Texas, USA, 13-15 September 2010.
7. Department for Transport Air Accidents Investigation Branch. Report on the accident to Boeing 777-236ER, G-YMMM, at London Heathrow Airport on 17 January 2008. Report, UK, February 2010.
 8. Sarkos C. Improvements in aircraft fire safety derived from FAA research over the last decade. Report, Washington, DC, May 2011.
 9. Watterwald M. *Water management within fuel tanks*. MSc Thesis, Cranfield University, UK, 2009.
 10. Guan T. *Fuel system water/ice management using OBIGGS*. MSc Thesis, Cranfield University, UK, 2014.
 11. Nou V. *Water management within fuel tanks using OBIGGS*. MSc Thesis, Cranfield University, UK, 2012.
 12. Akita K and Yoshida F. Bubble size, interfacial area, and liquid-phase mass transfer coefficient in bubble columns. *Ind. Eng. Chem*, 1974; 13.
 13. Jamialahmadi M, Zehtaban MR, Steinhagen HM, et al. Study of bubble formation under constant flow conditions. *Trans IChemE* 2001; 79: 523–532.
 14. Ramakrishnan S, Kumar R and Kuloor NR. Studies in bubble formation. *Chemical engineering science* 1968; 24: 731-747.
 15. Glycerine Producers' Association. *Physical properties of glycerine and its solutions*. New York, 1963.
 16. Kulkarni AA and Joshi JB. Bubble formation and bubble rise velocity in gas-liquid systems. *Ind. Eng. Chem*, 2005; 44: 5873-5931.
 17. BASF. n-Propanol. Technical leaflet, Ludwigshafen, March 2008.
 18. Zheng LB and Yapa PD. Bouyant velocity of spherical and nonspherical bubbles/droplets. *Journal of Hydraulic Engineering* 126: 11, November 2000.
 19. Coordinating Research Council. *Handbook of aviation fuel properties*. 3rd ed. Pennsylvania: Society of Automotive Engineers, 2004.
 20. Mehta K. *Water and ice management in fuel systems using OBIGGS*. MSc Thesis, Cranfield University, UK, 2013.
 21. Federal Aviation Administration. Water in aviation fuels. Advisory circular, August 1997.
 22. Drouet E, Poyet S and Torrenti JM, Temperature influence on water transport in hardened cement pastes. *Cement and Concrete Research* 2015; 76: 37-50.
 23. Burns M, Cavage WM, Hill R and Morrison R. Flight-testing of the FAA onboard inert gas generation system on an Airbus A320. Report, Federal Aviation Administration, Washington, DC, June 2004.
 24. Kholmer V, Grinis L. Gas-liquid interaction under vibration field effect. In: Eckhardt B. (eds) *Advances in Turbulence XII*, Berlin, Heidelberg, October 2009, pp923-923, Springer Proceedings in Physics.



DSPACE

<https://dspace.org/>

Analytical investigation into the effects of nitrogen enriched air bubbles to improve aircraft fuel system water management

Terada, Yuri; Lawson, Craig P.; Zare Shahneh, Amir

2017-11-19

SAGE

<http://dx.doi.org/10.1177/0954410017742422>

Terada Y, Lawson CP, Shahneh AZ, Analytical investigation into the effects of nitrogen enriched air bubbles to improve aircraft fuel system water management, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Volume 233, Issue 3, 2017, pp. 861-870