COLD FUEL TEST RIG TO INVESTIGATE ICE ACCRETION ON DIFFERENT PUMP INLET FILTER-MESH SCREENS

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Abstract

Feed pumps in aircraft fuel feeding systems deliver fuel from the fuel tanks to the engine frame. These pumps are protected by a weave type filter that stops debris in the tanks from entering the feed lines.

The presence of water in jet fuel is unavoidable. Any contaminating water could freeze during long flights at high altitudes and low temperatures. The resulting ice particles and snow clusters could block the filter protecting the pump as fuel is drawn into the pump through the feed line.

The process and effects of ice accretion on different mesh screens upstream of a centrifugal pump are being investigated. A suitable test rig has been designed to circulate Jet A-1 containing water/ice contaminants at cold temperatures through the strainers. An effective analysis of the experimental data, will aid to the development of an empirical model that will describe the phenomenon of ice accretion on the mesh.

1 Introduction

The presence of water in jet fuel has been a topic of concern since the 1950s when turbine-powered aircraft started to replace piston-powered aircraft, and a new type of fuel was required [1]. A number of incidents related to ice formation and accretion in the aircraft fuel system gave rise to research programmes, predominantly within military entities, in order to investigate the origins and behaviour of ice in jet fuel.

Water can be present in fuel in three forms: dissolved in the fuel, suspended in fuel as water-in-fuel emulsions, or free water. Dissolved water is invisible to the naked eye, and is considered a constituent of jet fuel that vaporises during combustion [2]. Suspended water appears as a dull, hazy, or cloudy appearance that takes time to coalesce or settle down. Free water, being denser than fuel, forms a separate layer at the bottom of fuel tanks. Water-in-fuel emulsions and free water are regarded as fuel contaminants.

Kerosene based fuels consist of three main types of hydrocarbons: paraffins, naphthenes and aromatics [1]. Past and present research demonstrates that the solubility of water in individual hydrocarbons appears to be more prominent in aromatics. The quantity of aromatic compounds in jet fuel is limited to a maximum of 25% by volume [3, 4]. In practice, the aromatic content varies from 12% to 24%. Given the higher solubility of water in aromatic compounds, it is believed that fuels with a higher concentration of aromatics display a higher degree of hygroscopicity.

The hygroscopic nature of jet fuel refers to its ability to attract moisture from the air or surroundings. The hygroscopicity of Jet A-1 is greatly dependent on the fuel temperature, a drop of 10 °C in water-saturated fuel, results in 15 to 25 parts per million (ppm) by volume of undissolved water coming out of solution [1].

On its own, the amount of hygroscopic water shed out in aviation fuel during a flight is not considered to be high, but it may accumulate over a number of flight operations if not managed properly. Adding other sources of water contamination [5], a flying aircraft may hold a considerable amount of water contaminant within its fuel tanks. At low temperatures, this water becomes ice and accretes to subcooled surfaces throughout the fuel system.

This paper focuses on the design and development of a cold fuel test rig. The rig will be utilised to investigate ice accretion on different mesh screens upstream of a centrifugal pump.

The fundamental theories and research on the crystallisation of water in jet fuel are briefly discussed. These theories, in conjunction with the Aerospace Information Report (AIR) 790C [6] and Aerospace Recommended Practice (ARP) 1401[1] [7], have been used to define specific test requirements that form the foundations of the cold fuel test rig design.

2 Icing and Nucleation of Water

The formation of ice crystals is a complicated process that has been the focus of numerous investigations for many years and remains a topic of current interest.

In accordance with Classical Nucleation Theory (CNT) [9], ice crystallisation involves a nucleation stage and a growth stage. There are two processes of nucleation:

- Homogeneous nucleation occurs when the water molecules combine to form an embryo. The critical-sized embryo or nucleus is in unstable equilibrium and energy is required to form a particular cluster of molecules; embryos smaller than the critical size shrink spontaneously, while embryos larger than the critical size grow spontaneously into a microscopic ice crystal [10, 11].
- Heterogeneous nucleation occurs when the crystallites of water molecules form on foreign particles such as dust, rust or dirt [12].

Homogeneous nucleation requires a greater degree of metastability than heterogeneous nucleation. Hence homogeneous nucleation happens at considerable lower temperatures than heterogeneous nucleation [11].

2.1 Homogeneous Nucleation of Water in Jet A-1 Fuel

Hobbs [11] reviews different studies on homogeneous water nucleation in air, establishing that for a droplet of radius of a few µm, homogeneous nucleation becomes significant in the range of -20 °C down to -50 °C.

As the temperature of jet fuel decreases, hygroscopic water from static fuel as found in storage tanks appears as a fine cloud of minute droplets of size diameter ranging from 5 µm to 30 µm [1]. The size of these droplets may be affected by conditions such as temperature, rate of cooling, type of fuel, and the relative humidity of the air above the fuel.

Depending on their size, droplets of water in aviation fuel can exist in a supercooled metastable state at temperatures below 0 °C. Murray *et al.* [13] investigated water drops deposited on a glass slide surrounded by a matrix of Jet A-1 fuel. Water droplets of above 10 µm in diameter within the fuel are submitted to sub-freezing temperatures. As the temperature was lowered at a rate of 10 °C min^{-1}, most of the droplets froze between -36 °C and -39 °C which is in good agreement with the data reported by Hobbs [11].

In a series of similar experiments, Carpenter *et al.* [14] examined three different batches of Jet A-1 fuels as they were cooled

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[1] Documents that define specific icing test procedures based on the extensive experience acquired by many fuel system companies following the conducting of icing tests over many years [8].

down to -70 °C. At temperatures below -44 °C, the water droplets in the fuel (of diameter ≤ 5 μm) started freezing as spherical particles. Results were in good agreement with the results reported by Murray *et al.* [13].

2.2 Heterogeneous Nucleation of Water in Jet A-1 Fuel

The introduction of foreign particles and external factors obscures and complicates the understanding of hygroscopic water nucleation in jet fuel. It adds many different parameters that are currently the subject of wide interest in many scientific studies as well as industry projects.

Aviation fuel in aircraft tanks contain traces of foreign particulate matter such as dust or rust particles, microbiological mats or sludges, crystals of benzene or paraffin, filter fibres and other impurities [5] that may provide crystallisation nuclei for the nucleation of supercooled water droplets dispersed in the fuel. Rough surfaces and surface defects in the system may also provide nuclei sites for crystallisation to occur.

Real aircraft feeding system components add factors such as turbulent flow, agitation, impurities and cold metal surfaces. Following a British Airways (BA) Boeing 777 crash landing at London Heathrow Airport in January 2008, the Air Accident Investigation Branch (AAIB) [15] final report reveals the formation of different forms of ice in the fuel. The report states that the formation of ice crystals in jet fuels are mostly cases of heterogeneous nucleation.

As reported by Lao *et al.* [18], ice accretion on a sub-cooled surface is elucidated by the Bergeron process[2]. This theory is confirmed with the observations made by Carpenter *et al.* [14]. Furthermore, observations during fuel system icing tests[3], have demonstrated that accreted ice on sub-cooled surfaces have very little adhesion strength. It takes minor fluid disturbances near the accreted ice to dislodge it from the surface. It is reasonable to postulate that ice suspended in fuel in the aircraft fuel system may be the result of dislodged ice previously accreted on the system sub-cooled surfaces.

The findings from the AAIB [15] are in agreement with Lao *et al.* [18], where ice is deposited on sub-cooled surfaces through the Bergeron process. This occurs at higher temperatures than the homogeneous nucleation of water droplets, indicating that the nucleation and crystallization of water in the fuel may be heterogeneous.

3 Ice Accretions on Metal Surfaces and Aircraft Fuel Systems

According to Hayashi *et al.* [16] the formation of frost can be divided in three stages, a) crystal growth period, b) frost layer growth period and c) frost layer full growth period. As the frost layer develops, it goes through these transformations. The frost thickness and surface temperature is gradually increased until the melting temperature of ice water is reached. Lüer and Beer [17] demonstrated in a series of experiments that the density and thickness of the frost surface layer depends on factors such as time, air temperature, air velocity, air humidity and surface temperature.

Lao *et al.* [18] observed deposition of water/ice on the surface of a sub-cooled aluminium block immersed in Jet A-1 fuel. The experiments were carried out in the cold tank

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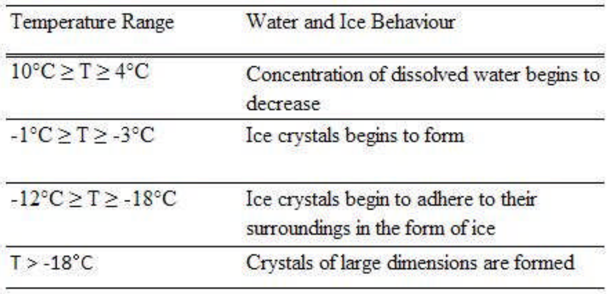
[2] Ice crystals grow through sublimation at the expense of the supercooled water droplets in the fuel.

[3] A number of projects on ice accretion have been taking place at Airbus for the past few years. A project that is currently being undertaken at Cranfield University in collaboration with Airbus is the EASA WAFCOLT project. The acronyms stand for European Aviation Safety Agency (EASA) – Water in Aviation Fuel under Cold Temperatures Conditions (WAFCOLT).

described in Section 4. The observed deposition formed a uniform thin layer of spherical droplets on the sub-cooled aluminium surface. The characteristics of the growth of this layer are analogous to that of the initial frost formation period described by Hayashi *et al.* [16]. However there was no evidence of frost layer growth on the sub-cooled aluminium surface. This may be due to the small and limited hygroscopic water contained in the closed fuel system, compared with an open system (as in the atmosphere).

The AAIB investigations [15] suggested that at fuel temperatures between -5 °C and -20 °C ice crystals tend to form in the fuel and adhere to fuel system components. Under certain conditions, a considerable amount of ice was found on the inner surfaces of the cold fuel test rig. A summary of significant temperatures found in their investigation is exhibited in Table 1. As seen on the fourth row, a “sticky region” of ice in fuel was observed between temperatures ranging from -12 °C to -18 °C. The ice adhered to fuel lines, strainers, and tank walls.

The AAIB also observed that fuel velocity, fuel temperature and water concentration in the fuel, play an important part in the thickness fluctuations of ice layers within the fuel feed lines [15]. These factors are comparable to those that have an effect on the thickness and density of a frost layer [17].



Temperature Range	Water and Ice Behaviour
10°C ≥ T ≥ 4°C	Concentration of dissolved water begins to decrease
-1°C ≥ T ≥ -3°C	Ice crystals begins to form
-12°C ≥ T ≥ -18°C	Ice crystals begin to adhere to their surroundings in the form of ice
T > -18°C	Crystals of large dimensions are formed

Table 1: Observations of water and ice behavior in jet fuel at low temperatures [6-7, 15]

The observations discussed in this section will be extrapolated to the investigations that are going to be carried out in the cold fuel test rig. The water concentration of the fuel, the velocity of flow through the mesh, and temperatures will be key variables during experimentation.

4 Development of the Cold Fuel Test Rig

4.1 Cold Fuel Test Rig Objectives

1. To determine the optimal mesh size that reduces the effect of ice accretion on the mesh, but also protects the pump from debris in the tank.

- By assessing the icing on the centrifugal pump remote inlet mesh screen and investigating ice accretion with different sized filter mesh screens. Thereby confirming there is no mesh blockage, nor adverse effect on pump performance.

- Various sizes of filter-mesh screens will be fitted in the cold fuel test rig and exposed to different conditions tailored to investigate the variation in the amount of ice accretion on the mesh screens, see Section 5.2.

2. To derive an empirical model that will describe the phenomenon of ice accretion on the remote inlet mesh screen.

- By measuring the amount of ice accretion on the filter-mesh screens, and analyse its variations with different key factors.

3. To investigate the effects that the Reynolds number, or fuel velocity passing through the filter-mesh screens has on the ice porosity on the mesh screens.

- To determine the compacting effect of the accreted ice by fluid flow variations.

4. To make sound observations concerning the nature of the ice accreted on the filter type mesh screen.

- Aim to make observations on the primary ice growth direction (transverse or longitudinal), the contour elongation of the ice crystals, and the conditions at which bridging[4] occurs.

4.2 Cold Fuel Test Rig Requirements

The test rig must meet the following requirements, with the aid of features detailed in Section 5:

1. Create a closed, re-circulating fuel system at constant fuel flow rates.

- The main benefit of a closed re-circulating system is to minimise the volume of fuel required for the experiments.

- A constant fuel flow rate through the different mesh screens is crucial in order to obtain consistent results

2. The fuel temperature must reach a minimum of -20 °C.

- To ensure that testing is performed within the "sticky region" of ice as discussed in Section 3.

3. Maintain a total (emulsion and dissolved) water concentration within the fuel i.e. no less than 90 ppm by volume [6, 7]. It must also contain several drain points for fuel sampling in both tanks.

- Consistent results in the expected range of water concentration will ensure that there is sufficient water in the system during testing.

4. Measure fuel temperatures at various locations in both tanks.

- To get a temperature profile of the fuel throughout the test rig. Ensuring good mixing and a homogeneous temperature field.

5. Monitor (visually) ice accretion on the protective filter-mesh screen.

- Make sound observations concerning the process of ice accretion on mesh strainers. It will also aid at determining the duration of icing tests.

5 Cold Fuel Test Rig Design

The schematic diagram shown in Figure 1 presents the general arrangement and layout of the cold fuel test rig. The basic arrangement of the test rig will be formed around three key components: two small fuel tanks of a combined fuel capacity of 50 L, and a small centrifugal pump that will circulate fuel at a maximum rate of 50 L min^{-1}.

The cold tank will contain the mesh screen under investigation, a pick-up line and an array of thermocouples. The thermocouples will be uniformly distributed throughout the volume of the tanks to obtain an accurate three dimensional temperature profile of the fuel.

The cold tank will be fuelled via the head tank through a pipe routed from the bottom of the head tank to the lid of the cold tank. The purpose of the head tank is to maximise the efficiency of the cold plates by a) keeping the cold tank full at all times, and b) actively avoiding air from entering the cold tank.

The mesh screen and pick-up line in the cold tank will be connected to the centrifugal pump outside by a pipe exiting through a seal in the top of the tank. The feed pump will deliver fuel through the head tank, and back to the cold tank via a hose, creating a closed, re-circulating system.

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[4] *Bridging* is the term used when the ice covering the wires of the mesh, start cohering to the ice from neighbouring wires, linking together to form a single solid ice formation.

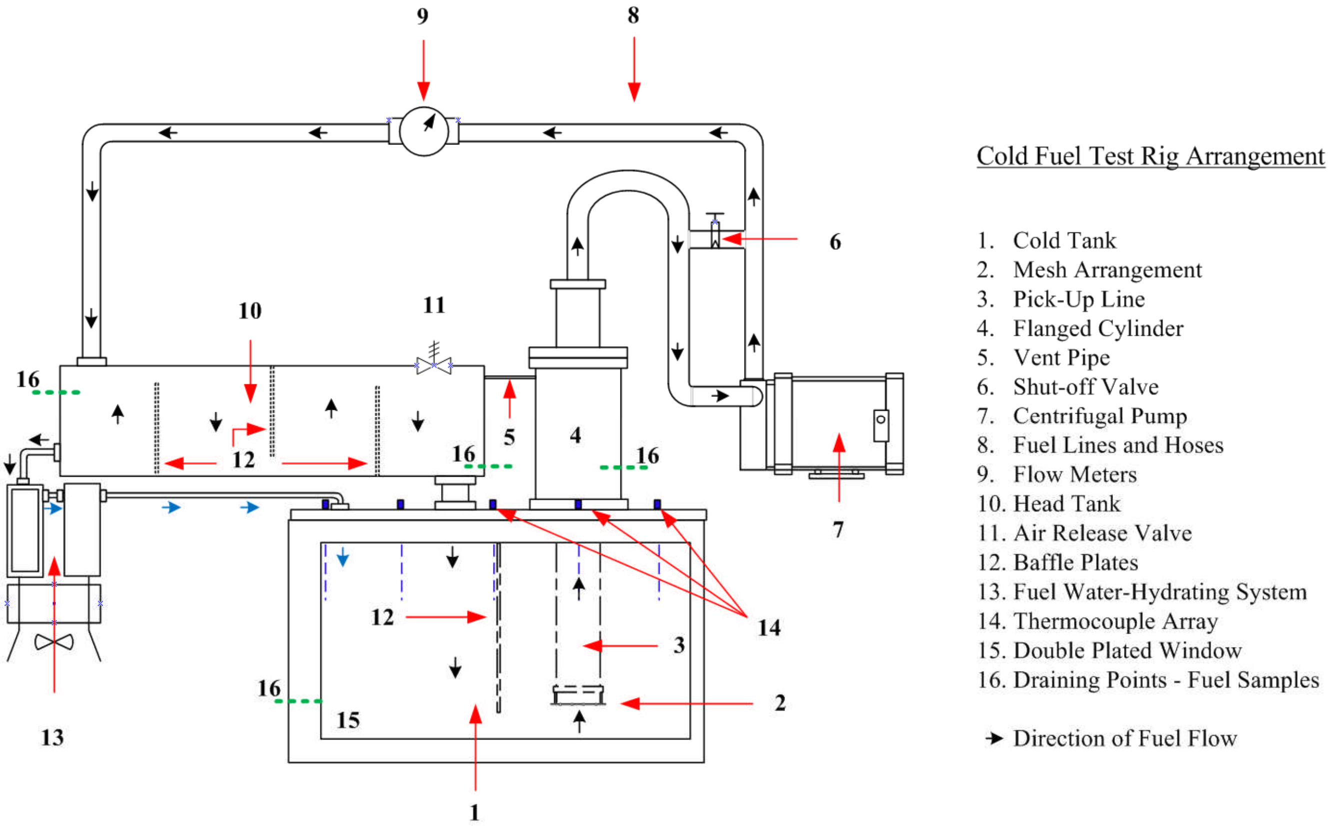

Fig. 1 – Schematic of experimental apparatus and equipment

Baffles will be mounted in both tanks to moderate and direct the flow of fuel and force air bubbles to the surface. The fuel flow will be directed through the tanks and around the cold fuel test rig on its way back to the pump.

Manual shut-off valves will be fitted throughout the test rig to direct the flow of fuel where required according to the different test stages.

Different flow rates will be achieved by means of a bypass and flow control valve fitted upstream of the centrifugal pump, on the delivery line exiting the cold tank, Flow conditions between the tanks will be monitored and recorded using flow meters and pressure sensors.

Thermocouples will be strategically installed throughout the cold and head tanks to obtain temperature profiles of the fuel passing through both tanks.

5.1 Cold Tank and Compressor Unit

The cold tank was used in a study by Lao *et al.* [18]. It consists of a 20 L glass-windowed aluminium tank with two cooling plates: a fixed bottom cooling plate, and a movable upper cooling plate. For the purpose of this investigation, a number of components will be mounted on a new lid for the cold tank. Therefore both cooling plates will be positioned at the bottom of the tank.

The coolant for the plates is supplied from a compressor positioned outside the test room. The cooling plates are operated separately from each other, allowing the temperatures to be set independently in each plate.

The compressor consists of a 2-stage cascade refrigeration system:

- A Hermitique compressor (CAE2471) using R134A as a refrigerant – high temperature stage.

- A Danfoss compressor (S-15G) using a binary refrigerant mixture – low temperature stage.

The compressor runs the Hermitique system for the lower temperature settings and the Danfoss system for the higher temperature settings.

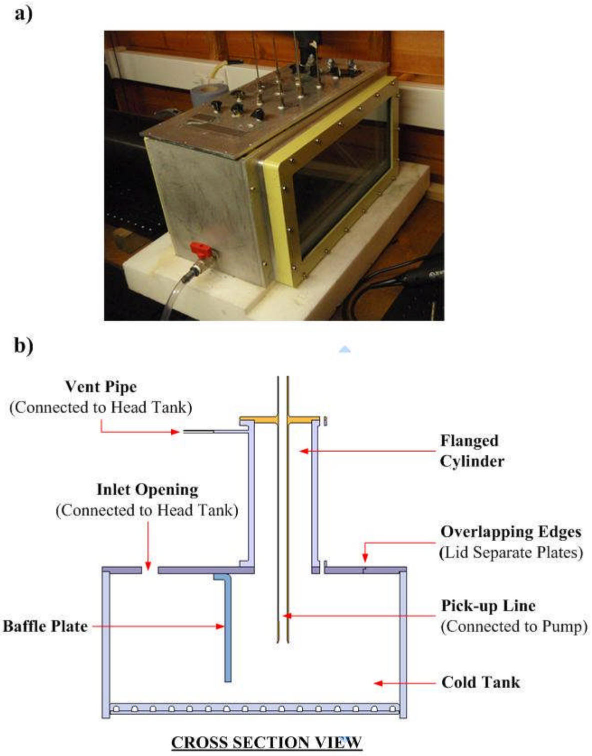

Fig. 2 – Cold tank: a) Cold tank as used for experimentation by Lao *et al.* [18], b) Cross section view of cold tank and new lid arrangement.

The cold tank (see Fig. 2) consists of welded aluminium panels, and has internal dimensions (H) 200 mm x (L) 500 mm x (D) 200 mm. It is water tight, and runs at ambient pressure. It has a removable lid, and is thermally insulated. For visualization purposes, windows of dimensions (H) 180 mm x (L) 400 mm are fitted in the side walls of the tank. These are double glazed windows with a 6 mm thick inner panel of toughened glass, a 10 mm air gap and a toughened glass outer panel that is 8 mm thick.

5.2 Lid and Mesh Assembly

The cold tank lid assembly is vital to the rig design as it incorporates most of the key components and interfaces. Firstly and foremost, the cold tank lid functions as a barrier to seal and maintain the desired cold tank internal environment. The lid is seated on a seal on the tank upper edge and fits around the entire perimeter. Physical pressure provided by a large number of bolts then activates this seal, making the tank water tight.

The lid is made up of three separate aluminium plates with overlapping edges that are independently sealed. This arrangement allows the lid to be assembled/disassembled rapidly in sections without having to interfere with the fixed geometry refrigerant inlet/outlet pipes. The refrigerant pipes pass through the lid via two grommet seals.

The lid assembly allows fuel to flow through the inlet hole connected to the head tank, then around the baffle (bolted to the lid) and into the meshed fuel intake before it is drawn out of the cold tank via the outlet pipe.

A flanged cylinder mounted on the lid allows the fuel intake and outlet pipe to pass through. Since the tank is filled to the top with fuel, the fuel continues into the flanged cylinder where the appropriate level is maintained using the vent pipe. This pipe will allow fuel fumes and fuel to outflow to the head tank. The outlet then exits the flanged cylinder and continues to the pump. The flanged cylinder is bolted to the lid and a seal ensures no fuel can leak though the interface. At the top, the flanged fuel outlet bolts onto the cylinder. These bolts can be quickly removed to gain access to the mesh by drawing out the pick-up line assembly.

The thermocouple array is mounted on the lid assembly. A number of threaded ports allow the thermocouples to be inserted into the tank without affecting the seal.

The mesh assembly is in the design stage. It is being designed to hold the mesh screen in place at a predetermined distance from the pick-up line intake. The mesh screens that are going to be investigated are identical to current types being used in commercial aircraft.

The mesh screens pump protectors commonly used in commercial aircraft are 4 and 8 mesh screens (also known as mesh *strainers*). These are square weave type filter type mesh screens with a linear pitch of four and eight wires per square inch respectively. An additional two mesh screens, counting six and ten wires per square inch are introduced in the mesh assembly design to assist in finding an empirical relation between ice accretion, and wires per square inch in the mesh.

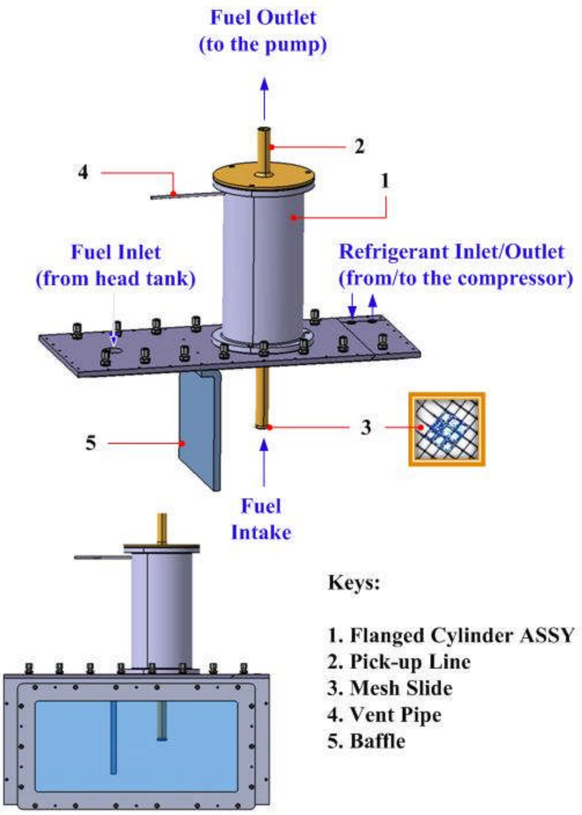

Fig. 3 – Cold tank lid design and assembly

5.3 Centrifugal Pump and Head Tank

The centrifugal pump is an ATEX rated pump which makes it suitable for pumping kerosene type fuel. Its delivery flow rate is 50 L min^{-1}, and runs on a 50 Hz, single-phase, 230 V-AC motor.

The pump can be divided into two main sub-assemblies: a fuel pump element and a motor. The fuel pump element comprises the following components:

- Rotor assembly
- Impeller assembly
- Inducer assembly
- Shaft

The pump element is assembled horizontally into a cast iron pump housing. The inducer assembly creates suction pressure that causes fuel to flow through the impeller assembly, which pressurises and forces the fuel out of the pump head.

The fuel pump head comprises a hollow body with an inlet and an outlet opening of 19.0 mm and 25.4 mm respectively.

As seen in Figure 1, the centrifugal pump (Item 2) is fitted outside the tanks. This is to avoid ice accretion on the metal surfaces of the pump, which would adversely affect the test by causing a significant decrease in water concentration within the fuel during testing.

The head tank is currently in the design phase. The designed tank has a capacity to hold approximately 30 L of fuel. It is a grade 304 stainless steel tank of inner dimensions (H) 150 mm x (L) 550 mm x (D) 400 mm, 3 mm thick. Three baffles are mounted in the head tank at a distance of 120 mm from each other.

Karl Fischer[5] tests will be carried out on fuel samples taken from a number of specially

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[5] The Karl Fischer method is a water determination test designed to determine water content in substances (i.e. Jet A-1), using the quantitative reaction of water with iodine

positioned draining points in the tanks. The tests will determine if the fuel and water are mixed in line with recommended practice [6, 7]. Hence the head tank design contains several fuel sample extraction points.

An air release valve installed at the top to allow air and kerosene fumes to bleed out of the tank automatically. The air release valve incorporates a diaphragm and a float and is capped by a rubber check valve. The diaphragm operates to allow air to bleed out from the tank; fuel loss is prevented by the float which lifts to close the valve. The rubber check valve prevents air from being sucked back into the head tank.

5.4 Fuel Water-Hydrating System

The addition of water to cold fuel is a complex process. Past experiments [15, 19] have shown that injecting pure water into cold fuel results in freezing of the nozzle on the injection device. Furthermore, a distinct suspended mass of water in the fuel forms as a result. In these investigations, two metered pumps were used to pump warm fuel and water into a single feed that was then introduced into the fuel in their test rig.

The fuel in the cold fuel test rig will be hydrated with warm water in a small reservoir connected to the head tank and the cold tank (Item 5 in Figure 1). Fuel will be drawn from the head tank via a hose. Once the hydrating process of Jet A-1 is finished, it will be directed to the cold tank and mixed with the larger quantity of fuel in the tank.

6 Discussion

Previous icing experiments, carried in the commercial aircraft industry [15, 20] have shown that small pitch mesh screens ice rapidly. By increasing the passage area (i.e. mesh openings, less wires per square inch), there may be a gradual improvement at the expense of allowing small debris coming through. Assuming the same testing conditions, more fuel may be able to pass through larger pitch mesh screens.

Other observations made by O’Connor and King [20] comprise:

- When the mesh was too close to the lips of the intake pipe, a circular “patch” covered in ice was formed. This “patch” had the same dimensions as the cross sectional area of the inlet pipe, whereas the rest of the mesh was ice-free. It is postulated that the patch is in the direct path of the fuel flow, and therefore it is more likely that it would ice up. Thus fuel flow rates and regimes through the mesh may have an effect on ice accretion on its surface.
- Provided that there is sufficient water in the fuel, varying the pitch of the mesh screen and increasing the area had some effect on the *time* required to block the mesh screen, but has no effect on the final result. On a moderate pitch mesh it may take more time for bridging to completely block each mesh cell.
- For larger pitch mesh screens (*pitch* ≥ 4 wires/in^2) the ice did not have sufficient strength to resist the suction and continually broke away. Even though considerable ice accumulated, complete blockage and bridging did not occur [15, 20].

The existing literature is based solely on experimental observations. Therefore it is difficult to foresee the type of mathematical relationship between the screen passage area and fuel flow conditions, or between screen passage area and the amount of ice accumulated on its surface at set conditions.

Fluid flow factors affect the ice accretion in fuel systems. Bends, pipe joints and misalignments, or any fuel flow steps found in fuel lines, promote ice accretion. Curvilinear pipework tends to accumulate more ice than straight sections. This can be attributed to changes in the fuel Reynolds number and fuel

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and sulphur dioxide in the presence of a lower alcohol (such as methanol) and an organic base (such as pyridine).

flow regimes (turbulent, transitional and laminar) as it travels through the fuel system, or test rig.

Considering the observations on the effect that the Reynolds number has on the ice accretion and accumulation in pipes [15, 19], or even the thickness and density of frost layers [17], it is believed that changing the velocity of the fuel flow passing through the mesh screens may also have an effect on the ice accumulated on their surface.

The AAIB [15] also observed the formation of a form of ice clusters that are prone to adhere to surfaces and to each other. The term used is “sticky ice” and it is described as soft snow. An interesting observation made is that although a large snow ball found downstream of a fuel pipe in their test rig, no pressure drop was detected across the section of the pipe. The fuel was still flowing at a set rate through the “sticky ice”, which indicates that the ice may have a very loose structure i.e. high porosity.

The test rigs used for the experiments described in this section [15, 19-20], include actual components taken from specific aircraft fuel feeding systems, i.e. DC-8 and Boeing 777. Reducing the scale of cold fuel test rigs, as the one proposed in this paper, will relieve the level of complexity of experimentation and analysis of results.

7 Concluding Remarks

Icing and nucleation of water in aviation fuel are active topics of research in the aircraft industry and research community.

Experiments carried out in the aircraft industry involve full-scale and partially full-scale tests rigs, built with real aircraft fuel system components. This is mainly because standard practices recommend duplicating the actual aircraft fuel system as close as possible. The conditions and parameters set during experimentation would be as close as those experienced by an aircraft in flight.

The phenomena of ice formation and accretion in these test rigs may be closer to real aircraft scenarios, but introduces uncertainty and complexity. It is therefore difficult to draw sound conclusions that can facilitate the understanding of hygroscopicity or icing phenomena in aviation fuel.

Crystals and clusters of ice are observed at temperatures close to the freezing temperature of water, which indicates the heterogeneous nucleation of hygroscopic water.

Experiments carried out within the confines of a laboratory involve considerable smaller test rigs that give the user control over a small range of parameters. In the research community, experiments have been performed with jet fuel in a controlled and clean environment. Such conditions favour the homogeneous nucleation of hygroscopic droplets of water in jet fuel.

Ice accretion on sub-cooled surfaces within a laboratory environment can be elucidated by the Bergeron process, where ice crystals growth is due to the sublimation at the expense of the supercooled water droplets in the fuel.

The design of the cold fuel test rig has been determined by geometric and environmental factors that are believed to promote the icing of mesh screens upstream of a centrifugal pump. The small test rig design has the capability to obtain and record empirical data.

The strategy of experimentation on the test rig is being optimized using dimensional analysis to reduce the number of key variables [21]. Through the use of dimensional analysis and careful design of experimentation, the analysis of experimentation data will generate a set of equations associating the amount of ice accretion with key variables.

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