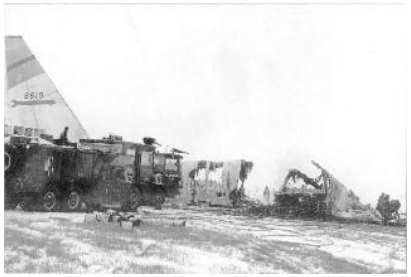
Icing in Aircraft Fuel Lines

Federal Aviation Administration

[4]



[3]

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Introduction

- **This project is a continuation of a masters thesis from Rutgers University**
- **The purpose is to further understand ice accumulation in jet fuel such as that which caused flight accidents.**

Background

- **B52 accident (1958)** [3]
  - Fuel pump screen clogged with ice.
  - Over 200 previous “cause unknown” accidents later attributed to fuel icing.
  - Fuel Heaters and Icing Inhibitors were introduced
- **Boeing 777 engine rollback (2008)** [2]
- **Boeing 777 accident (2008)** [2]
  - Blockage of the FOHE from ice.
- **A330 engine rollback (2009)**

Objective

- **Perform experiments to better understand the collection of ice in fuel pipes.**
  - Material Dependence
    - How does the type of material effect ice accumulation?
    - How does the roughness of pipe material effect ice accumulation?
  - Temperature Effects
    - Is there a preferred temperature for ice accumulation?
  - Effects of Flow Rate and Flow Structure
    - How does turbulence such as from a defined region of recirculation effect ice accumulation?
    - What is the effect of a Reynolds Number variation on ice accumulation?
  - Heat Transfer Effects
    - If there is a greater heat transfer from the fuel pipe, will ice accumulation be greater?
  - Contamination
    - What is the effect on ice accumulation of common contaminants?

Experimental Setup (Altitude Chamber)

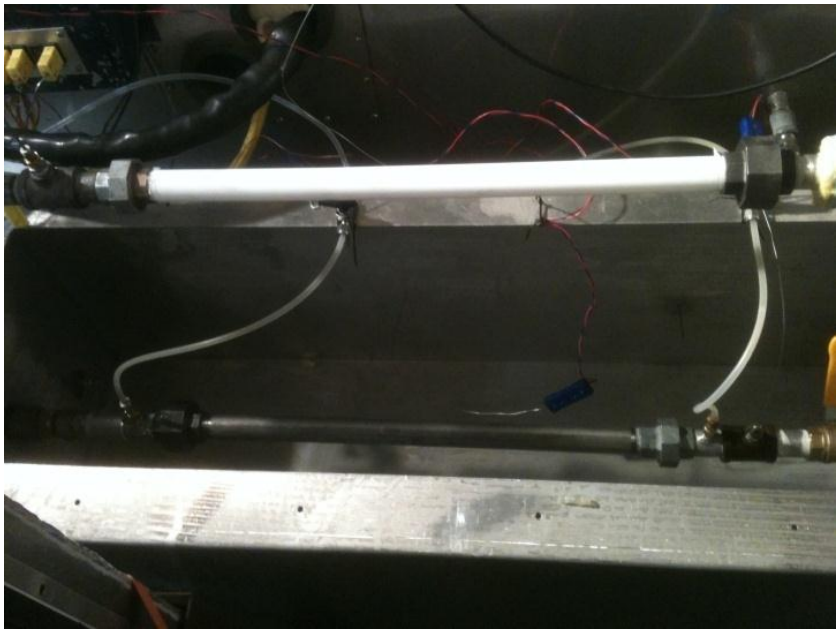
- **Temperature Potential: -51.1C**
- **Current fuel storage within the chamber: 115 gal.**
- **Pressure Potential: 2.73psi (40,000ft)**
- **Humidity Control**

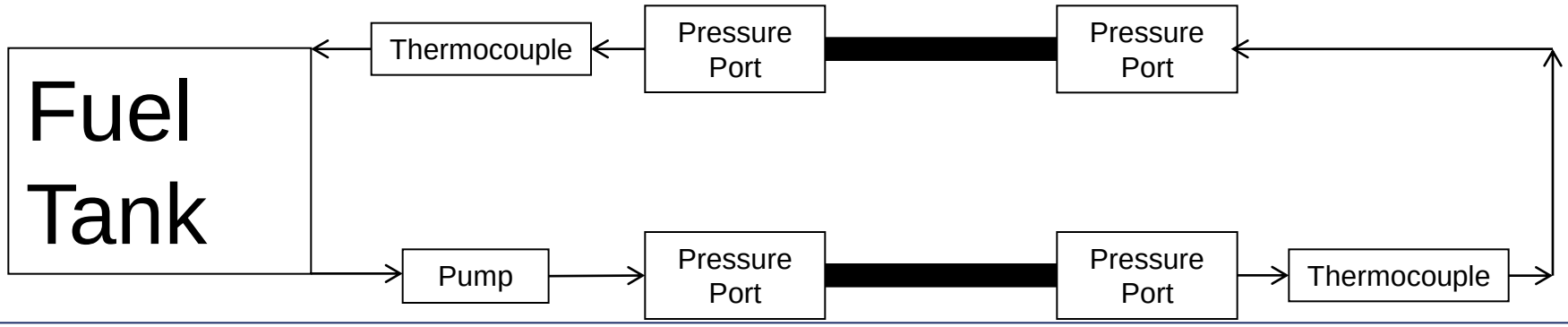
Altitude Chamber

Experimental Setup (test sections)

- **Test sections**
  - Each test pipe was fitted with ports for differential pressure measurement.
  - Each pipe had a type T thermocouple port downstream of the test area.
  - Each test pipe was easily removable for visual observation and ice quantity measurement.

Experimental Setup (test sections)

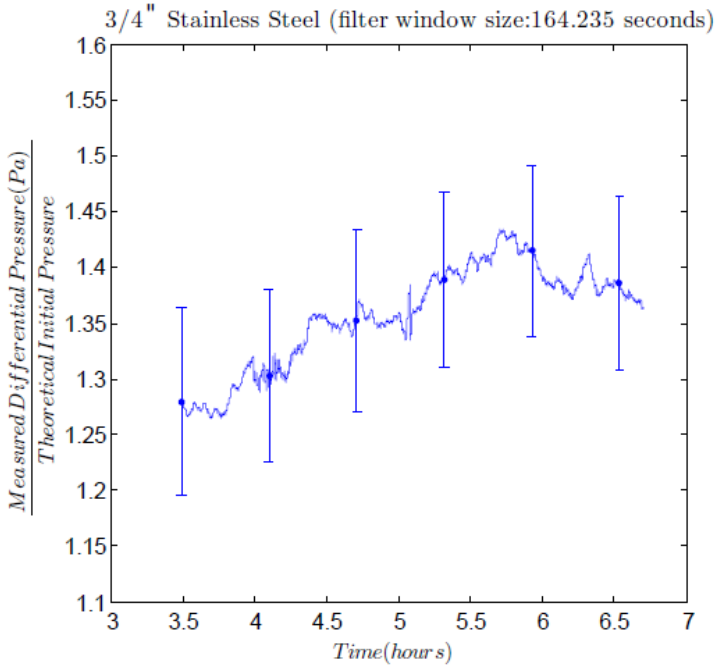




Experimental Setup (Fuel Preparation)

- Jet A-1 fuel was saturated at about 21.5 Celsius with approximately 25mL of free water in a tray at the bottom of the fuel tank.
- The fuel was filtered for particles and water prior to each test.

Typical Test Results



Reynolds Number:.....2031.3346
Test Temperature:.....-9.3119 °C [-6.38 -13.14]
Initial Temperature:.....21.405 °C[22.905 18.905]
Test Duration:.....2.4714 hrs
Flow is diverted prior to: -9.3119 °C
Pressure Increase:.....0.0063987 $\frac{Pa}{m \cdot sec}$[0.0064308 0.0063667]
H_2O collected from pipe: 0.25 mL [0.25097 0.24903]

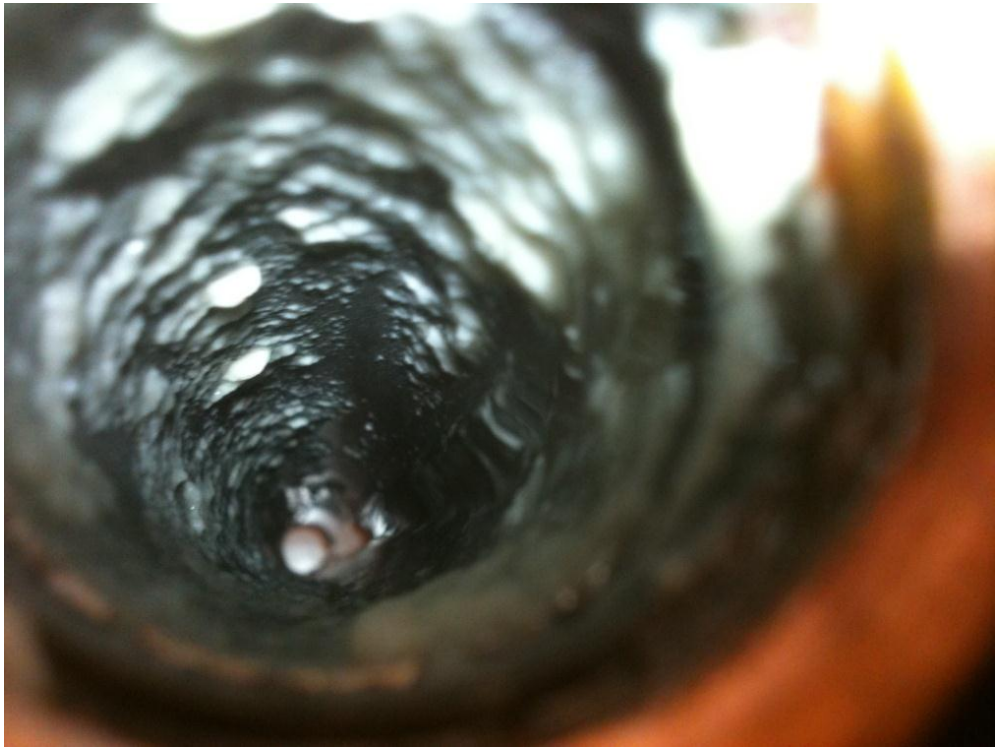
Note: The figures displayed here do not necessarily correspond to a single test

Initial conditions variation

- **Initial conditions in the test pipe**
  - Fuel flowed through the test pipe as the fuel cooled to the test temperature.
  - Air was present in the test pipe as the fuel cooled to the test temperature.
  - Stationary fuel was present in the test pipe as the fuel cooled to the test temperature. (in this case there was a small air gap in the pipe also.)
  - Air was present in the test pipe except for a defined region which was sprayed with water

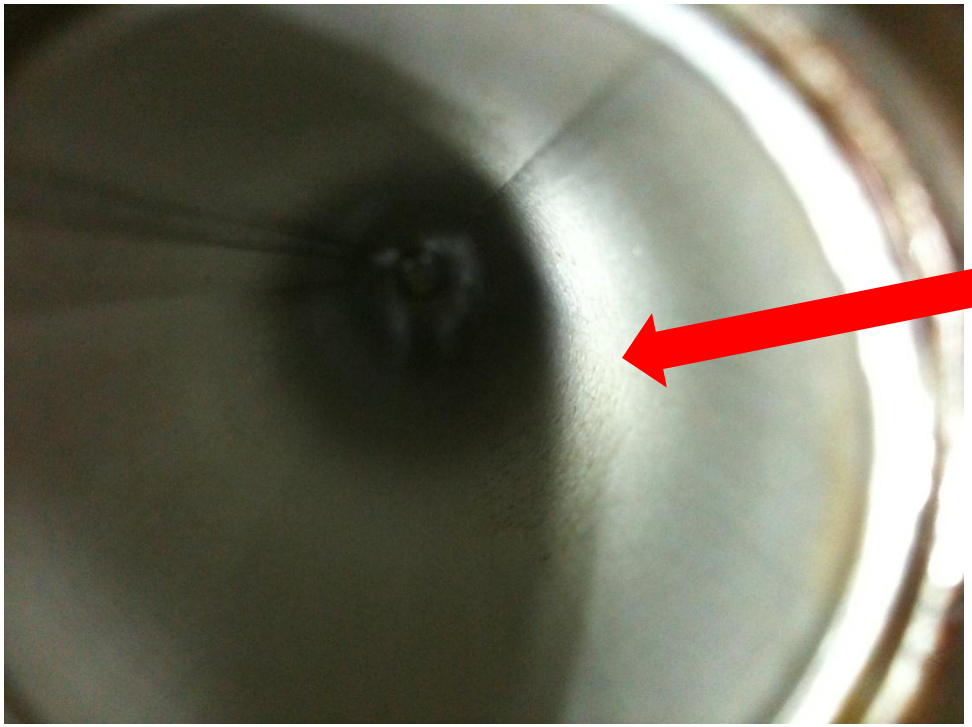
Results of initial conditions variation

- Fuel flow through the test pipe as the fuel cooled to the test temperature.



Results of initial conditions variation

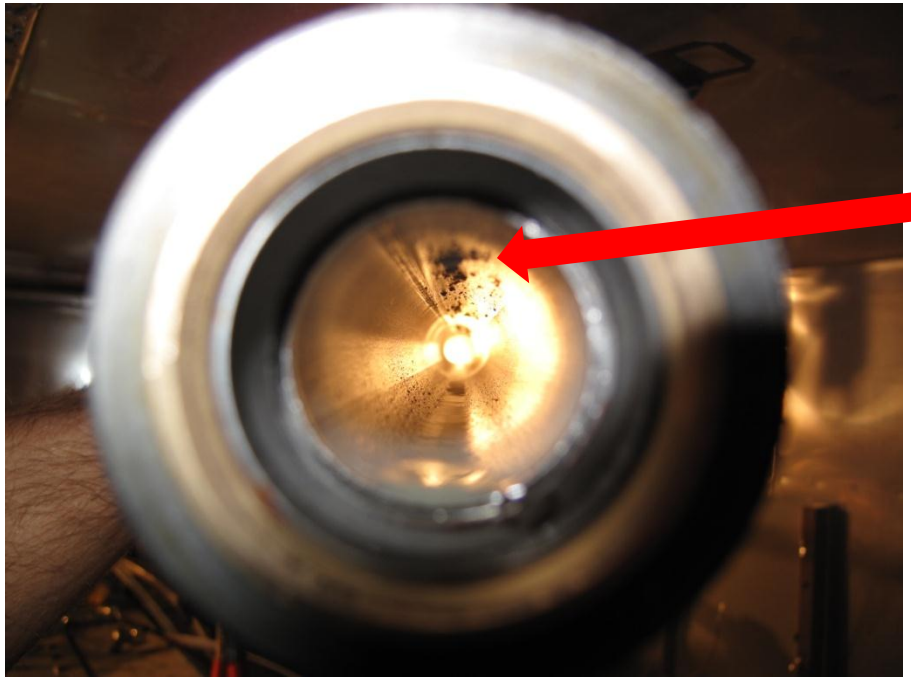
– Air in the test pipe as the fuel cooled to the test temperature.



A noticeable amount of ice but less than the previous condition.

Results of initial conditions variation

– Stationary fuel in the test pipe as the fuel cooled to the test temperature. (in this case there was a small air gap in the pipe also.)



Ice along the top of the pipe where air was trapped

Results of initial conditions variation

– Air in test pipe except for a defined region that was sprayed with water

Before

After

Note: A clear image of the other side of the pipe was not taken after the test where water was not sprayed but it had a lack of ice accumulation

Conclusion for initial conditions variation

- The softer ice may stick to the pipe material but it stuck to hard ice substantially more.
- The case that fuel flowed continually through the flow loop as the fuel cooled was chosen for further quantitative tests.

Test Conditions Variation

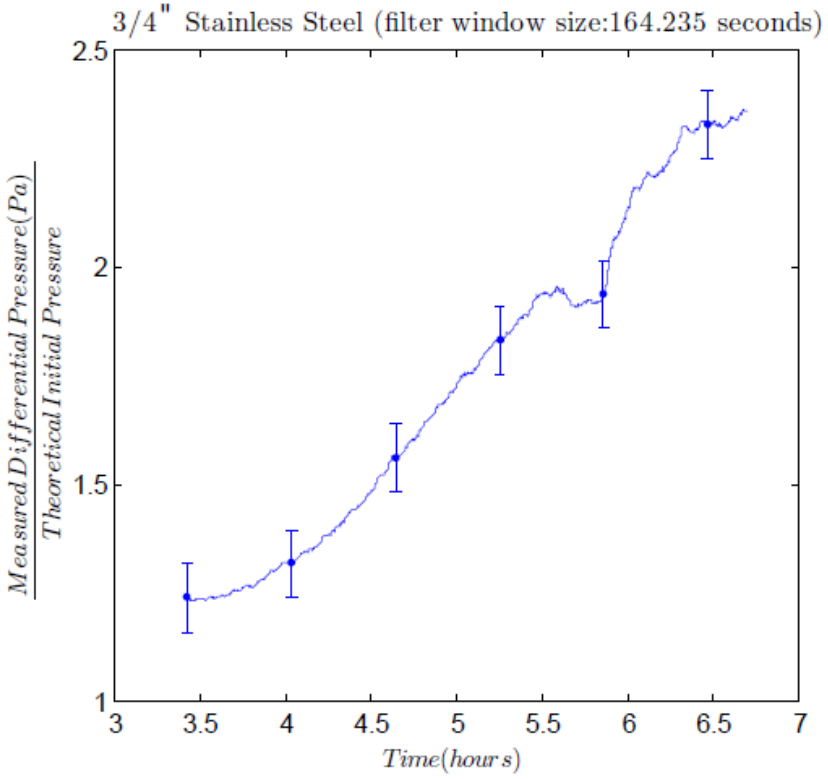
- **Repeatability**
  - Repeatability tests were done at a Reynolds number of 8362 and temperature of -11 °C
- **Variation of Reynolds Number**
  - ≈3150 to ≈13000
  - This Re regime covered the range that a commercial airliner may typically encounter.
- **Variation of Temperature**
  - ≈ -7 °C to ≈ -20 °C
  - Boeing attributed -5 °C to -20 °C to be the temperature range that had sticky ice. [2]
- **Variation of Heat Transfer from the Pipe**
  - Insulated pipe or not insulated pipe
  - This variation was done because of what was unintentionally found in earlier tests.
- **Fuel Contaminants (Each previous contaminant wasn't completely removed before adding the next one)**
  - Dust
  - Excess water
  - Ground up aluminum
  - Ground up steel
  - Ground up Polyurethane insulation

Results of test condition variation (Repeatability)

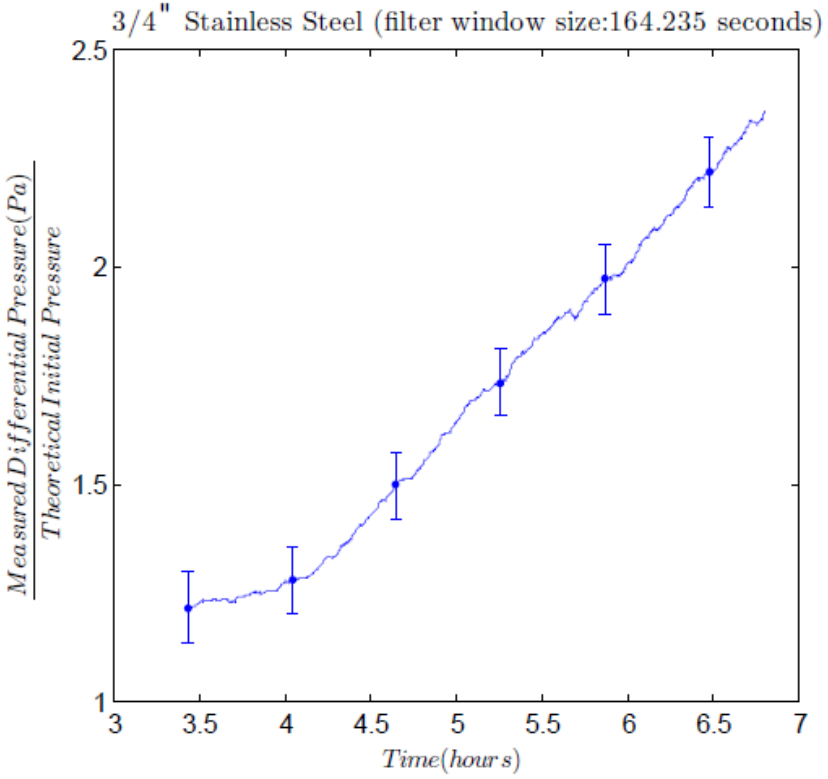
Test 1

Test 2

Results of test condition variation (Repeatability)

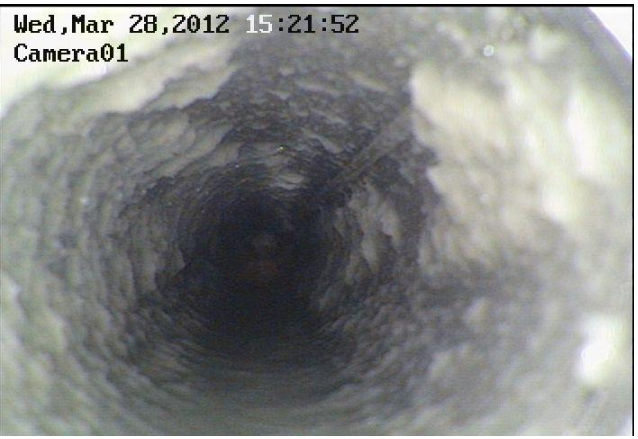


Test 1



Test 2

Results of test condition variation (Reynolds Number)



Re: 4000

Re: 8362

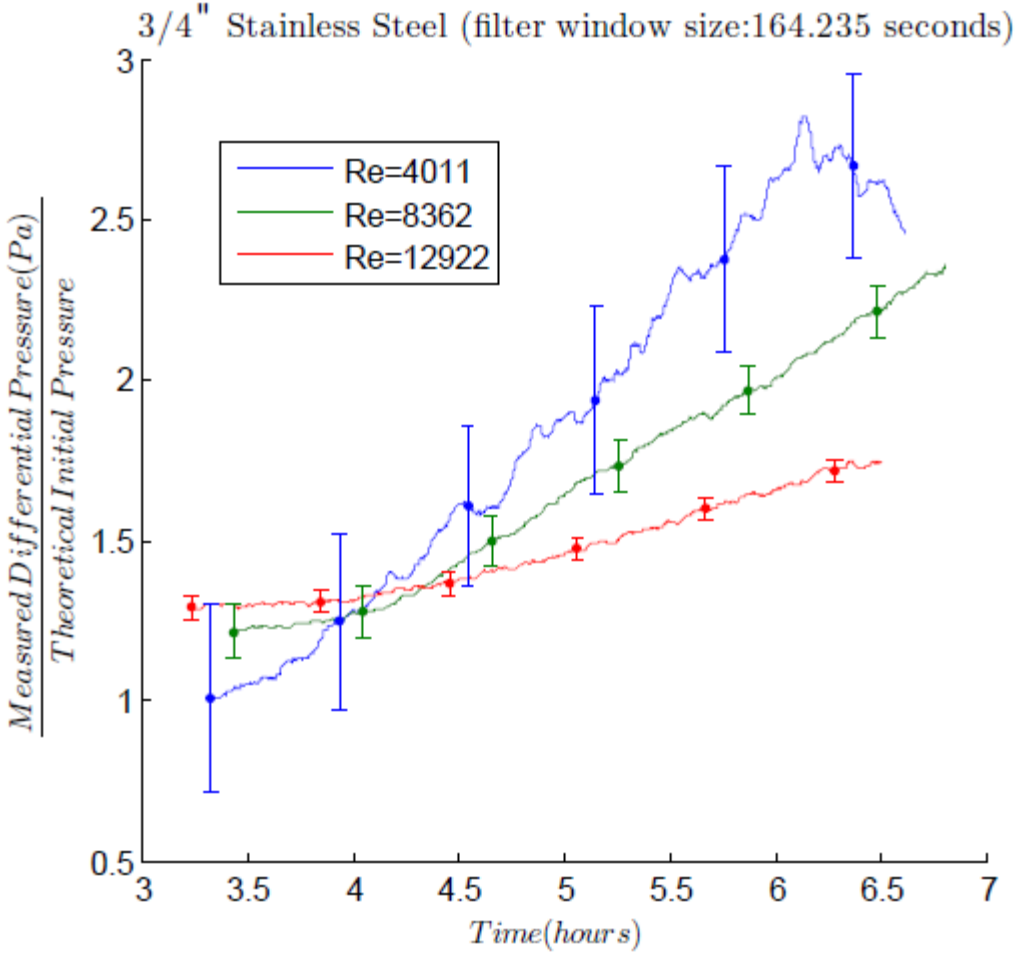
Re:12922

Thicker ice

Thinner ice

-11 °C

Results of test condition variation (Reynolds Number)



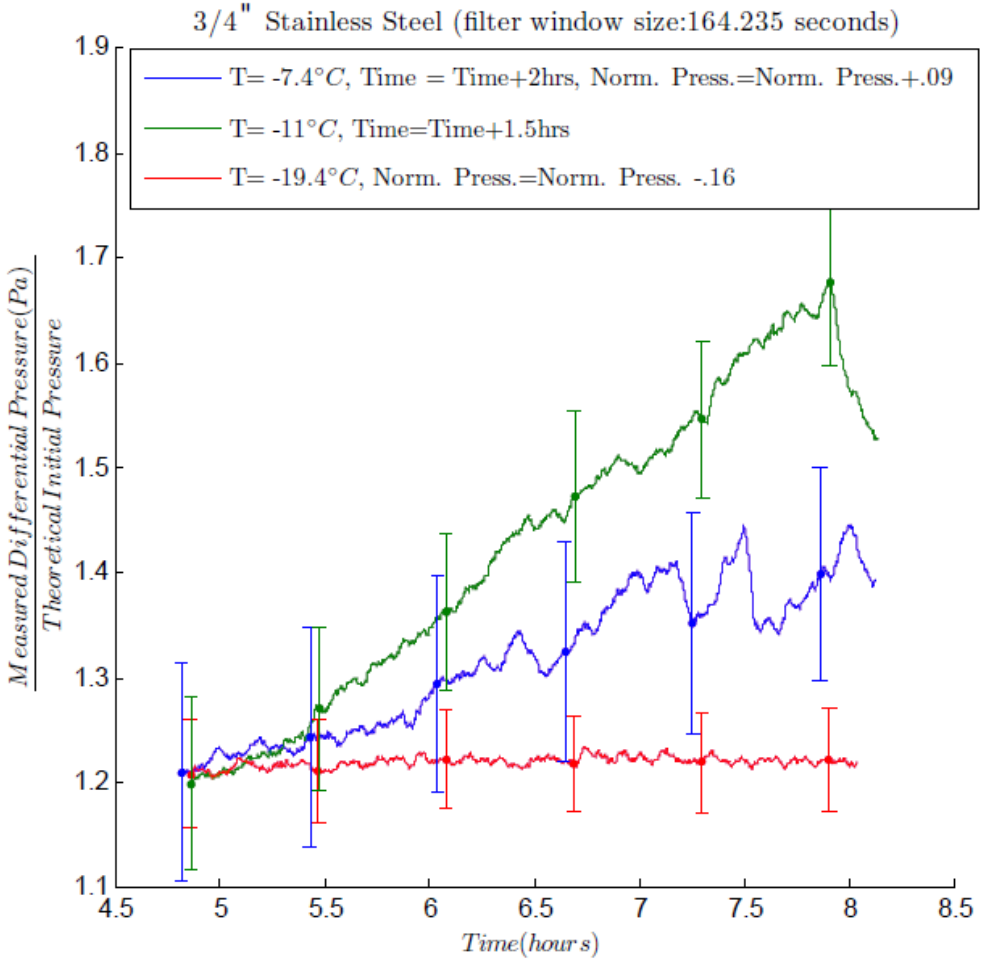
Results of test condition variation (Temperature)

-7.4 °C

-11.24 °C

-19.35 °C

Results of test condition variation (Temperature)

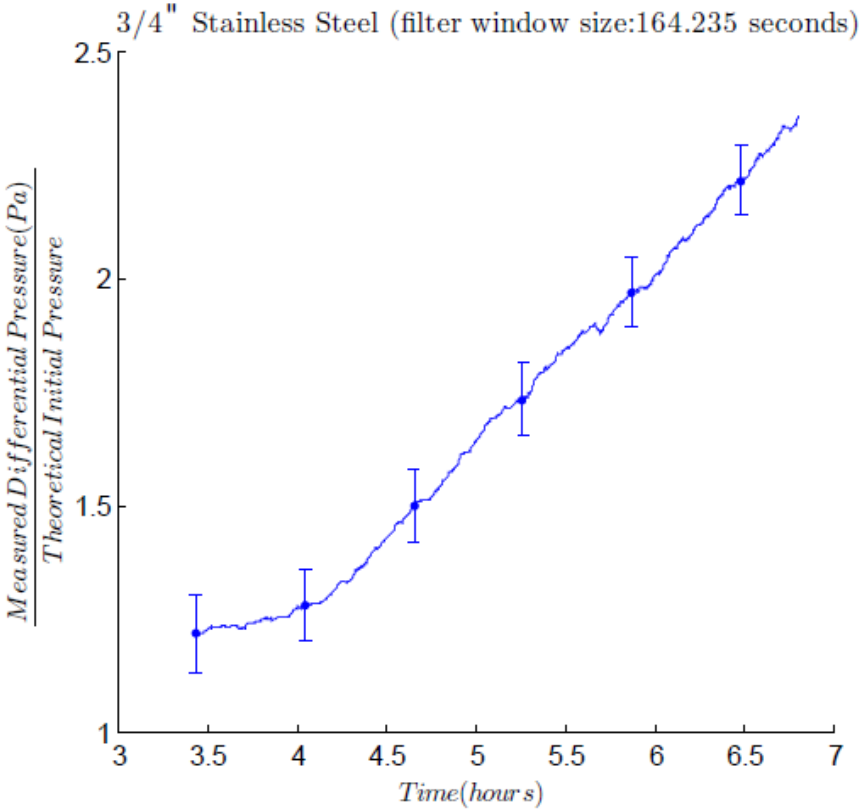


Results of test condition variation (Heat Transfer)

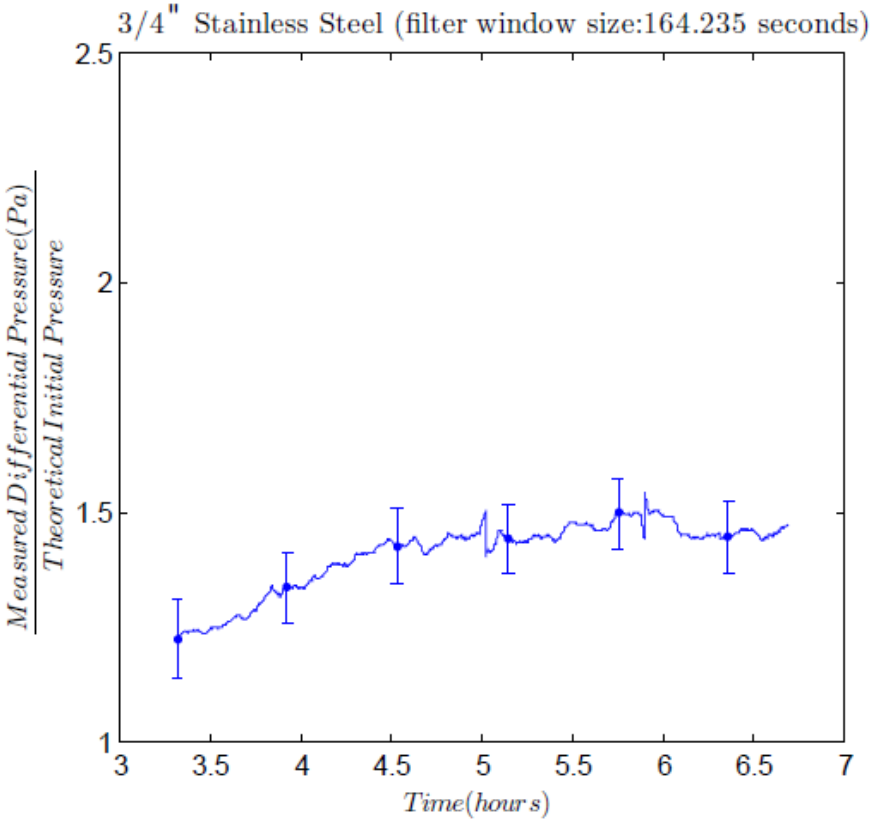
Un-Insulated

Insulated

Results of test condition variation (Heat Transfer)



Un-Insulated



Insulated

Results of test condition variation (Contamination)

Fuel with the mystery contaminant

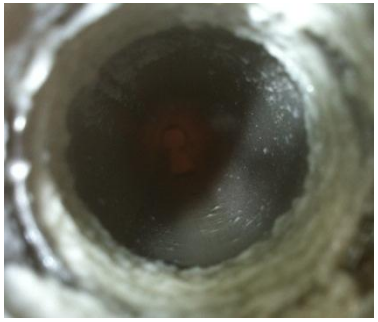
Dust | Excess Water | Ground Aluminum | Ground Steel | Ground Polyurethane Insulation

Summary of results for test condition variations

- Repeatability was shown to exist visually with the pipe images and quantitatively with pressure increase.
- Higher Re decreased total accumulation because of an increase in shear stress
- The ice accumulated the most at -11 °C.
- A greater heat transfer from the pipe increased ice accumulation.
- Fuel contaminants contribute to ice accumulation.

Other observations

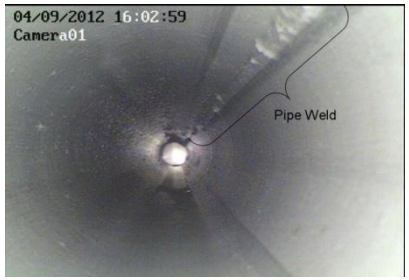
- **Contamination increases ice accumulation.**



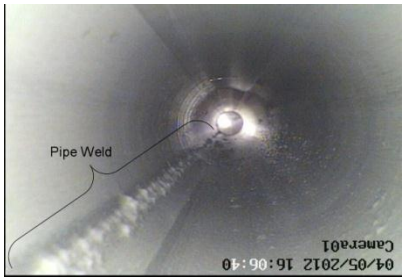
Stainless Steel

PTFE

- **Ice accumulated more on pipe welds than elsewhere in the pipe**



Pipe Oriented right-side-up



Pipe Oriented up-side-down

Overall Summary of Results

- **Initial Conditions Variations**
  - The softer ice may stick to the pipe material surface but it stuck to hard ice substantially more.
- **Pipe Configuration Variations**
  - Materials with a greater adhesion force to water will therefore collect more water and have a greater potential to collect soft ice.
  - Pipe geometry variations lacked a defined region of ice accumulation immediately downstream.
- **Test Conditions Variation**
  - Higher Re decreased total accumulation because of an increase in shear stress.
  - The ice accumulated the most at -11 °C.
  - A greater heat transfer from the pipe increased ice accumulation.
  - Fuel contamination contributes to ice accumulation.

Future Work

- **Continue to test various contaminants to determine what may have been the cause of a decrease in accumulation.**
- **Test actual aircraft fuel pipes. (The same material but thinner)**

Questions or Suggestions?

- **Contact**
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  - Thomas.ctr.Maloney@faa.gov

Citations

- [1] Lao, Liyun, David Hammond, Colin Ramshaw, and Hoi Yeung. *Part 2 Ice Accretion*. Rep. 2011. Print.
- [2] Department for Transportation, Air Accident Investigations Branch. *Report on the Accident to Boeing 777-236ER, G-YMMM, at London Heathrow Airport on 17 January 2008*. Working paper. Crown, 2010. Print.
- [3] Scotty, Leonard R. "Above and Beyond: Fire and Ice." *History of Flight, Aviation, Space Exploration | AirSpaceMag.com*. Web. 14 Nov. 2011. <http://www.airspacemag.com/military-aviation/Above--Beyond-Fire-and-Ice.html>.
- [4] *BA38*. 2008. Photograph. *Wikipedia, the Free Encyclopedia*. By Marc-Antony Payne. Web. 14 Nov. 2011. <http://en.wikipedia.org/wiki/File:BA38_Crash.jpg>.