Effect of Cabin Pressure on the Piloted Ignition of Combustible Solids

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Motivation

- Fires in pressurized vehicles (aircraft, spacecraft or submarines) are extremely hazardous
  - Small compartments
  - Difficulty to escape
- Emphasis on fire prevention:
  - Material flammability
  - Effect of environmental conditions (oxygen concentration, pressure, radiant heat flux, etc) on ignition
Today’s Talk

• Understand the physical mechanisms responsible for ignition of solid combustibles under low pressure

• Aircraft cabin pressure is typically pressurized to a "cabin altitude" of 8000 feet or less (~ 75 kPa)

• Are reduced pressure environments a higher fire risk?
  ▫ Piloted ignition experiments at low P
    • Forced Ignition and Spread Test (FIST) apparatus at UC Berkeley to analyze material flammability
  ▫ Analytical explanation of results

[Images of fire at different pressures: 12 psi and 6 psi]
Lower ambient pressure can be found at...

- High Altitude
  - Lhasa, Tibet – 3,650 m population 2,500,000
  - Quito, Ecuador – 2,850 m population 2,500,000
- Inside Aircraft
- Inside Spacecraft
Cabin Environments

- Typical Aircraft Cabin
  - Quito, Ecuador 2,850 m
  - Lhasa, Tibet 3,650 m

- Shuttle/Mir/ISS
- Shuttle EVA Preparation
- Early Apollo Design
- Skylab
- Mercury/Gemini/Apollo

- Decompression sickness
- Hypoxia
- Flammability

- Normoxic Equivalent
- Hypoxic Boundary
- Historical Designs

Cabin Total Pressure, kPa vs. Cabin Volume Percent Oxygen
How does a solid fuel ignite?

Piloted ignition process:

1. Solid heating & pyrolysis
2. Mixing of gaseous fuel and air
3. Chemistry: fuel/air mixture reaches lean flammability limit at high temperature igniter
4. If sufficient pyrolysis gases are generated: a diffusion flame will anchor on solid (burning) → critical mass flux at ignition
Possible Fire Scenario

- Heat source: electronic component overheating
- Fuel: polymeric materials used in panels, blocks, covers
- Ignition source: spark from electrical arching
Forced Ignition and Spread Test (FIST)

Variables:
- air flow velocity
- incident heat flux
- ambient pressure

Material: PMMA

Measure:
- $T_{surface}$ vs. time $\rightarrow t_{ig}$, time to ignite
- Mass vs. time $\rightarrow (dm/dt)_{tig}$ mass loss rate at ignition
FIST Apparatus
Video of Test
Experiment Example

- 100 kPa (Raw Data)
Experimental Results

- Pressure Comparison: 55, 83 & 100 kPa (Raw Data)
Experimental Results

- Ignition Delay & Mass Loss Rate at Ignition vs. Pressure

\[ m''_{ig} = 0.005 \cdot P + 1.483 \]

\[ t_{ig} = 4.604 \cdot P + 355.32 \]
Visual Observations

• Different surface behavior: bubble formation, size and bursting characteristics

3 psi (21 kPa) 12 psi (83 kPa)

• Flame establishment over solid surface also different

3 psi (21 kPa) 12 psi (83 kPa)
Effect of Pressure (1)

- Ignition delay time, $t_{ig}$:
  - $t_{ig} = t_{heating} + t_{mixing/transport} + t_{induction}$

- Heating time: convective heat loss over flat plate
  - Forced flow: $h \propto \frac{1}{2} \frac{Pr}{Re^{1/3}}$
  - Natural convection: $h \propto \frac{Gr}{Pr^{1/4}}$
  - Mixed flow:
    - $Re = \frac{\rho UL}{\mu}$, $Re \sim P$
    - $Pr \neq f(P)$
    - Ideal gas: $Gr \sim P^2$
    - $h \sim P^{1/2}$

As pressure decreases, convective heat loss of material to surroundings is lower → heats more rapidly
Effect of Pressure (2)

- Mixing/transport time: Mass loss rate at which a flammable concentration (LFL) is obtained at the pilot

Simplified Analysis: Boundary Layer – Integral Method

- 3rd order polynomials for velocity, temperature and species profiles:
  \[
  \frac{u}{U_\infty} = \frac{3}{2} y - \frac{1}{2} \left(\frac{y}{\delta}\right)^3 \quad \frac{T - T_0}{T_\infty - T_0} = \frac{3}{2} \frac{y}{\delta_T} - \frac{1}{2} \left(\frac{y}{\delta_T}\right)^3 \quad \frac{Y_F - Y_{FO}}{Y_{F\infty} - Y_{FO}} = \frac{3}{2} \frac{y}{\delta_c} - \frac{1}{2} \left(\frac{y}{\delta_c}\right)^3
  \]

- Integrate BL Eqns. → analytical expressions for hydrodynamic, thermal and concentration BL thicknesses:

![Graph showing velocity and concentration boundary layers](image)

\[
\delta = \sqrt{\frac{280 \nu x}{13 U_\infty}} \approx 4.64 \sqrt{\frac{\nu x}{U_\infty}}
\]

\[
\delta_T = \left[\frac{10a x \delta}{U_\infty} \left(1 - \frac{x_T}{x}\right)\right]^{1/2}
\]

\[
\delta_c = \delta \left\{13D \left[1 - \left(\frac{x_c}{x}\right)^{3/4}\right]\right\}^{1/3}
\]
Simplified Analysis
Heat Transfer Coefficient

- \( h \approx \frac{k}{\delta_T} \)

- At the sample location, \( h \) decreases by 13\% when the pressure is reduced from 100 kPa to 75 kPa
Simplified Analysis
Species Concentration

• Reduced pressure leads to a thicker species boundary layer

\[ \frac{Y_F}{Y_{F0}} = 1 - \frac{3}{2} \frac{y}{\delta_c} + \frac{1}{2} \left( \frac{y}{\delta_c} \right)^3 \]
Simplified Analysis

- To determine mass loss rate:

\[ \dot{m}'' \approx -\rho D \left( \frac{\partial Y_F}{\partial y} \right)_y = \frac{3}{2\delta_e} \rho D Y_F \left( 1 - \left( \frac{y}{\delta_e} \right)^2 \right) \]

- At lower P, required mass flow rate of fuel to reach lean flammability limit at igniter location is reduced
Comparison of Trends

- Mass Loss Rate at Ignition vs. Pressure

**Equation:**

\[ m_{ig} = 0.005 \cdot P + 1.483 \]

**Legend:**
- Diamonds: Experiments (Burning)
- Orange dotted line: Analysis (Flash Point)

**Graph Details:**
- Heat Flux: 16 kW/m²
- Air Flow Velocity: 0.4 m/s

**Axes:**
- X-axis: Ambient Pressure (kPa)
- Y-axis: Mass Flow Rate at Ignition (g/sm²)
Current Work

Fire Dynamics Simulator (FDS) 2D model

- PMMA is irradiated under a prescribed heat flux → the solid decomposes and the products of the pyrolysis ignite in the gas phase.

- Premixed flame appears in the gas phase
- Flame ‘jumps’ on to solid fuel surface
- Diffusion flame anchored on solid surface travels

HRR

Temperature
Current Work

- Fire Dynamics Simulator (FDS) 2D model
  - Heat release rate/volume:
Summary & Conclusions

• Experimental results from piloted ignition show that $t_{ig}$ & $m_{ig}$ decrease with pressure:
  - At 75 kPa, $\Delta t_{ig} = -15\%$
  - $\Delta m_{ig} = -7\%$

• A theoretical explanation provides insight on the effect of pressure on:
  - Heat transfer coefficient
  - Mass loss rate required to reach a flammable mixture

• Next steps include developing a numerical model using FDS to compare to experiments

• Overall, a reduction in ambient pressure leads to an increased fire risk
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