Particle Image Velocimetry and Hot Wire Anemometry for Investigation of Premature Flow Separation in a Generic Aircraft Cabin Mock-Up

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Introduction

• Passenger comfort plays an increasing role for marketing of modern aircrafts.

• Passenger comfort is strongly influenced by structure and intensity of cabin air flow in combination with the resulting temperature distribution.

• Each new cabin layout has to be checked for compatibility with thermal requirements by the manufacturers for each custom layout.

• Reliable CFD simulations are a mighty tool to allow for corrections of thermal design already in early stage of design process.

• Discrepancies between experiment and CFD especially when it comes to premature jet separation.

• Validation of numerical methods, i.e. turbulence models, radiation models, mesh parameters, differencing schemes necessary.

• Here: Validation employing a generic aircraft cabin model for fast simulations allowing for comparison of numerical parameters at well defined boundary conditions.
Generic Aircraft Cabin Mock-Up for Study of Mixed Convection

A380

Generic Model
Generic Aircraft Cabin Mock-Up

- Steel Frame
- Thermal Insulation
- Viewport
- Floor Heating Panels
- Overhead Bin Contour (heated)
- Air Inlets
- Air-Outlet

Volume: 7,700 l
Volume flow rates: 20 – 90 l/s
Air exchange rates: 9 – 42/h
Experimental Techniques

• Smoke tracking for visualization of global flow patterns.

• Particle Image Velocimetry (PIV) for determination of fluid velocity (2C2D).

• Hotwire-CTA for frequency and length scale analysis.

• Infrared thermography for determination of thermal boundary conditions.

• Temperature measurements with thermocouples for measurement of fluid temperature fields.
Experimental Parameters

- Observation plane (PIV and CTA): Central cross cut
- Temperature: Cooling case
- Volume flow rate: 20 l/s
- Air exchange rate: 9.4/h
Premature Jet Separation under Thermal Load

Simulation of the cooling case by heating up the mock-up with the heating panels on the contours and the floor.

Mass Flow: 20 l/s

\[ \Delta T = \langle T_{\text{jet}} - T_{\text{Cabin}} \rangle = 12^\circ C \]
\[ \langle T_{\text{cont}} - T_{\text{jet}} \rangle = 19^\circ C \]
\[ \langle T_{\text{floor}} - T_{\text{jet}} \rangle = 19^\circ C \]

\[ T_{\text{jet}} = 22^\circ C \]

“Cooling Case”
Critical Temperature Difference for Premature Separation

\[ Ec = \frac{v^2}{c_p | T_m - T_w |} \]

Cooling Case: \( Ec = 27.5 \)

\( Ec < 64 \)  
Separation on contour

\( Ec > 64 \)  
Separation at ceiling
Setup for Particle Image Velocimetry

Seeding:
- Oil droplets (DEHS), $<d> = 1 \, \mu m$

Camera:
- 3 PCO Sensicam (QE),
- Zeiss Planar T* 1.4/50
- Frame rate (double frame): 2.5 Hz

Laser:
- Nd:YAG (Quantel Twins/Twins B)
- Energy: $2 \times 320 \, mJ \, @ \, 532 \, nm$, Pulse duration: 5 ns
Flow Separation under Thermal Load, Measured by PIV

Simulation of the cooling case by heating the mock-up with the heating panels on the contours and the floor.

Mass Flow: 20 l/s

\[<T_{\text{cont}}-T_{\text{jet}}>- 19^\circ\text{C}\]
\[<T_{\text{floor}}-T_{\text{jet}}>- 19^\circ\text{C}\]

\[T_{\text{jet}} = 22^\circ\text{C}\]

\[\Delta T = 12^\circ\text{C}\]

“Cooling Case”

Ec = 27.5
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\[ \Delta T = 12^\circ \text{C} \]

„Cooling Case“

\[ \text{Ec} = 27.5 \]
Separation – Mean Velocity Profile

\[ N = 894 \]
\[ Q = 20 \text{ l/s} \]
Separation – RMS of Velocity Field

$N = 894$
$Q = 20 \text{ l/s}$
Set Up for Hot Wire CTA

- Hot wire probe (tungsten):
  - $l = 2 \text{ mm}$
  - $\varnothing = 5 \text{ um}$
  - Orientation parallel to x-axis
- CTA mode
- Overheating ratio: 1.5
- Subtraction of mean velocity signal
- Registration of the fluctuation signals
  - Recording time $> 20 \text{ min}$
  - Sampling rate $> 200 \text{ Hz}$
- Evaluation: Autocorrelation Function (ACF), Power Spectral Density (PSD)
Hotwire CTA – Measurement Position Separation Point

Cooling Case Average
Autocorrelation at Separation Point

Motion of separation line takes place periodically
**Hot wire CTA – Dynamics of Separation Line**

Power Spectral Density at the Separation Point

\[ f_{\text{max}} \approx 0.006 \text{ Hz} \]
\[ \tau_{\text{max}} \approx 160 \text{ s} \]
Hotwire CTA - Influence of the Mock-Up Length

- Motion periodical, regardless of number of cells.
- Correlation and frequency increase with number of symmetry cells.
Hot wire CTA - Influence of the Mock-Up Length

Resonance damped and shifted to lower frequencies with decreasing cell number.

Separation dynamics is determined by longitudinal modes.
Separation for Symmetrical Thermal Boundaries

Viewport Thermally Insulated

- Motion of separation point *quasiperiodic* for symmetric boundary conditions.
- Statistical temporal behaviour.
Separation for Symmetrical Thermal Boundaries

Viewport Thermally Insulated

- Motion of separation point \textit{quasiperiodic} for symmetric boundary conditions.
- Temporal evolution stochastical.
Summary

1. Premature separation in the case of $Ec < 64$ (Reference case: $Ec=27.5$).
2. Periodical motion of separation point with period duration of $\tau = 160\; s$.
3. Motion is more pronounced with increasing number of symmetry cells.
4. Motion of the separation point due to longitudinal modes, sensitive to thermal boundaries.
5. Asymmetrical thermal boundaries cause periodicity of separation line motion.
6. For symmetrical thermal boundaries, quasiperiodic motion with a statistical temporal behaviour is observed.