Conditioning in an airliner

Félix Dabonneville
Dept. of Energy Sciences, Faculty of Engineering, Lund University, Box 118, 22100 Lund, Sweden

ABSTRACT
Modern civil airliners fly at high altitude to obtain ideal conditions of flights. It permits to avoid turbulences of the relief, wind instabilities, and to decrease the air density, thus the resistance of air.

However, the plane inboard needs to be heated since the temperature decrease with the altitude. At supersonic speeds, due to important viscous friction effects, the surface of the plane is warmer and the inboard needs to be cooled.

NOMENCLATURE
\( a \) sound velocity, \( m/s \)
\( C_p \) specific heat, \( J/(kg.K) \)
\( d \) thickness, \( mm \)
\( h \) heat transfer coefficient, \( W/(m^2.K) \)
\( K_n \) Knudsen number
\( k \) thermal conductivity, \( W/(m.K) \)
\( L \) length, \( m \)
\( M \) molar mass, \( (kg/mol) \)
\( M_a \) Mach number
\( N_a \) Nu
\( p \) pressure, \( Pa \)
\( q \) heat flux, \( W/m^2 \)
\( R_e \) Reynolds number
\( R_u \) universal gas constant, \( J/(mol.K) \)
\( r \) recovery factor
\( T \) temperature, \( °C \)
\( U \) velocity, \( m/s \)

Greek Symbols
\( \rho \) density, \( kg/m^3 \)
\( \sigma \) Stefan-Boltzman constant, \( kg \cdot s^{-3} \cdot K^{-4} \)
\( \varepsilon \) emissivity
\( \mu \) dynamical viscosity, \( Pa.m/s \)

INTRODUCTION
This project will focus on the external wall temperature and the heat exchanges through a simplified insulated wall, both at subsonic and supersonic speeds, in an airliner. We will show results for different thickness of insulation.

The references for these two cases, subsonic and supersonic, will be respectively the Airbus A340 and the Concorde SST. The cruise conditions of flight will be considered.

PROBLEM STATEMENT
Figure 1 shows a schematic drawing of the heat conduction through the aircraft hull.

The known data are the comfort temperature inside the airplane \( T_i \), the cruise speed \( U_f \) and the cruise altitude \( z \). The thickness of the insulation \( d \) has to be chosen. The external wall temperature \( T_w \) and the internal wall temperature \( T_{wi} \) have to be calculated.

The figure 2 shows the heat exchanges through the aircraft hull.

The governing equation to be solved is the heat balance:

\[
q_{conv,i} = q_{cond} = q_{conv,e} + q_{rad}
\] (1)

with
heat flux by convection between the internal wall and the air inside the plane
$q_{\text{cond}}$ heat flux by conduction through the insulation
$q_{\text{conv,e}}$ heat flux by convection by the external wall and the ambient air
$q_{\text{rad}}$ heat flux by radiation between the external wall and the ambient air.

**LITERATURE SURVEY**

The warming up of the airframe of the Concorde SST has been published on the web site www.concordesst.com [1], as shown on the figure 3 below.

![Airframe Temperature (at Mach 2.0)](image)

The temperature at the middle of the airliner 92 °C will be our reference for the result of the external wall temperature $T_{\text{we}}$ on the supersonic model.

**PROJECT DESCRIPTION**

**Subsonic airliner**

The Airbus A340 is a standard airliner flying under the transonic speed. Its cruise conditions of flights are at 13 000 meters at Mach 0.83 [2].

The physical properties of the atmosphere at 13 000 meters high are:

- $T_f = -56$ °C.
- $p = 16 850$ Pa.
- $\mu = 1.5 \times 10^{-5}$ kg/m.s
- $k = 0.02$ W/(m.s)
- $C_p = 1005$ J/(kg.K)
- $Pr = 0.73$
- $\rho = \frac{p}{R_f T} = \frac{p}{R_u T} = \frac{M_{\text{air}}}{M_{\text{air}}}$

with

- $M_{\text{air}} = 28.96$ g/mol
- $R_f = 8.3144 J/(mol.K)$

$T \text{ in Kelvin}$

$=> \rho = 0.267 \text{ kg/m}^3$

To obtain the absolute velocity of the airplane, we need to calculate the speed velocity:

$$a = \sqrt{\gamma R_u T} = 295 m/s$$

Thus,

$$U_f = Ma.a = 244 m/s$$

We consider the heat flux at high fluid velocities, and we cannot neglect the viscous friction on the surface of the aircraft.

To know if we are in a continuum flow case, we need to calculate the Reynolds number then the Knudsen number.

We use as a characteristic length the half of the length of the plane: $L = 30$m.

$$Re = \frac{\rho UL}{\mu} = 2.76 \times 10^8$$

Thus,

$$Kn = \frac{Ma}{\sqrt{Re}} = 5.0 \times 10^{-5}$$

$Kn$ is much lower than 0.3, then we are in a continuum flow case.

For a turbulent flow over a flat plane, the boundary layer heat transfer for high velocities is calculated with the following method:

$$q_{\text{conv,e}} = h(T_u - T_{aw})$$

where

- $T_{aw}$ adiabatic wall temperature, °C
- $T_u = T_f + r \frac{U_f^2}{2C_p} = -29.63°C$
- $r = Pr^{1/3} = 0.9$

$Nu = \frac{hL}{k} = 0.037 Pr^{1/3} (Re^{1/5} - 23550) = 230560 \Rightarrow h = 76.85$

The heat balance with the other heat exchanges will be studied after analyzing the external heat exchange by convection in the supersonic case as follow.

**Supersonic airliner**

The SST Concorde flew from 1976 to 2003. After the accident of 2003, all airplanes has been stopped.

The cruise conditions of the SST Concorde were at 16 000 meters at Mach 2.00 [3].

The physical properties of the atmosphere at 16 000 meters high are:

- $T_f = -56$ °C.
- $p = 10 350$ Pa.
- $\mu = 1.5 \times 10^{-5}$ kg/m.s
- $k = 0.02$ W/(m.s)

To obtain the absolute velocity of the airplane, we need to calculate the speed velocity:

$$a = \sqrt{\gamma R_u T} = 295 m/s$$

Thus,

$$U_f = Ma.a = 244 m/s$$

We consider the heat flux at high fluid velocities, and we cannot neglect the viscous friction on the surface of the aircraft.

To know if we are in a continuum flow case, we need to calculate the Reynolds number then the Knudsen number.

We use as a characteristic length the half of the length of the plane: $L = 30$m.

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Thus,

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$Nu = \frac{hL}{k} = 0.037 Pr^{1/3} (Re^{1/5} - 23550) = 230560 \Rightarrow h = 76.85$

The heat balance with the other heat exchanges will be studied after analyzing the external heat exchange by convection in the supersonic case as follow.
- $C_p = 1005 \text{ J/(kg.K)}$
- $Pr = 0.73$
- $\rho = \frac{P}{R_T} = 0.166 \text{ kg/m}^3$

The speed and main velocities are respectively:
- $a = \sqrt{\kappa T_T} = 295 \text{ m/s}$
- $U_f = Ma.a = 602 \text{ m/s}$

As for the subsonic case, we consider the heat flux at high fluid velocities, and we cannot neglect the viscous friction on the surface of the aircraft, which will be even more important here since the airplane speed is higher.

To know if we are in a continuum flow case, we need to calculate the Reynolds number then the Knudsen number.

We use as a characteristic length the half of the length of the plane: $L = 30m$.

$$Re = \frac{\rho UL}{\mu} = 2.12 \times 10^8$$

Thus,

$$Kn = \frac{Ma}{\sqrt{Re}} = 1.4 \times 10^{-4}$$

$Kn$ is much lower than 0.3, then we are in a continuum flow case.

The boundary layer heat transfer for high velocities:

$$q_{conv,x} = h(T_w - T_{aw})$$

with

$$h = 15 \text{ W/(m}^2 \text{.K)}$$

$$T_w = 20^\circ C$$

The value of $h$ is an average standard value of internal convection coefficient inside buildings in horizontal direction.

The heat transfer by radiation between the plane and the atmosphere:

$$q_{rad} = \varepsilon \sigma (T^4_w - T_f^4)$$

where

$$\varepsilon = 0.04$$

$$\sigma = 5.67 \times 10^{-8}$$

The emissivity value corresponds to highly polished aluminum, used in aircraft. Since the emissivity is very low, we could neglect the term of heat transfer by radiation in the heat balance, since it will affect less than 1% the final results.

We have now enough known values to solve the heat balance (1) and to obtain the heat flux, the inside and the external wall temperatures. We will study the two cases for different thickness of insulation: 50 mm, 100 mm and 200 mm.

The results are shown in the table below:

<table>
<thead>
<tr>
<th>Airliner</th>
<th>Mach</th>
<th>Insulation thickness mm</th>
<th>Q W/m²</th>
<th>Twa °C</th>
<th>Twi °C</th>
<th>Twe °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concorde</td>
<td>2.00</td>
<td>50</td>
<td>29</td>
<td>-29.63</td>
<td>18.00</td>
<td>-29.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>15</td>
<td>-29.63</td>
<td>19.02</td>
<td>-30.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>-13</td>
<td>105.95</td>
<td>20.85</td>
<td>105.40</td>
</tr>
<tr>
<td>Concorde</td>
<td>2.00</td>
<td>50</td>
<td>49</td>
<td>105.95</td>
<td>23.27</td>
<td>105.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>-25</td>
<td>105.95</td>
<td>21.67</td>
<td>105.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>-13</td>
<td>105.95</td>
<td>20.85</td>
<td>105.40</td>
</tr>
</tbody>
</table>

Q is the need of heating if the value is positive and the need of cooling if it is negative.

In the subsonic case, it seems reasonable to use 100mm of insulation: it is a compromise between reducing the need of conditioning and gaining more useable space inside the plane.

In the supersonic case, two times more insulation is needed to obtain the same flux than in the subsonic case. The external wall temperature is higher than our literature reference (92°C) of 14%.

Another criterion is needed to decide which thickness of insulation we should use:

The noise level inside the plane: the insulation will reduce the noise level made by the engines for the comfort of people on board.
DISCUSSION

This project gave coarse values of the airframe temperature on an airliner and the heat flux through the insulation. The thickness insulation must be decided to evaluate the needs of conditioning all over the plane and then to design the air conditioning system. It has been shown that the inboard of the Airbus A340 needs to be heated whereas the inboard of the Concorde SST needs to be cooled, due to the viscous friction, an important effect for a supersonic aircraft. Nowadays, in standard subsonic airliner, the conditioning is realized by taking the warm air from the engine compressors and cooling it in heat exchangers with cold air before send it inboard. It is more complicated for a supersonic airliner as the Concorde: the cold air is not enough to cool the conditioning air, due to the high external wall temperature. Thus, a heat exchanger with the cold fuel is added on the conditioning system [3].

REFERENCES

http://www.concordesst.com/


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