Thermal simulation of a complete vehicle using manikin models

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SIMVEC – Simulation und Erprobung in der Fahrzeugentwicklung
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Motivation – Promoted Project STROM

BMBF (German Federal Ministry of Education and Research):
Sponsorship in the topic "Key Technologies for Electromobility (STROM)"

Project group:
Innovative air conditioning and thermal comfort concepts for the range optimization of electric vehicles (E-Komfort)

Time span: 3 years up to June 2014

Partners/ Competence:
- Volkswagen AG → Vehicle OEM
- Fraunhofer IBP → Measurement of thermal comfort (DRESSMAN)
- P+Z Eng. GmbH → Thermal cabin simulation (THESEUS-FE + OpenFOAM)
Overview

1. Creation of baseline thermal simulation model
2. Simplified simulation model
3. Concepts for zonal climatization
4. IR radiators and local thermal comfort
5. Validation of coupled cabin simulation
Creation of baseline thermal simulation model

**Starting point:**
- FE model for side impact crash simulation
- material names, thicknesses, density
- connector elements: welding spots, adhesives

**Model enhancement:**
- Remeshing of missing parts
- Volume meshing of important parts
- Thermal contacts and bridges
- Cavity convection effects
- Thermal/solar radiative heat transfer
- Creation of a thermal material database: $\rho$, $\lambda$, $c_p$, $\varepsilon$, $\alpha$, $\tau$

*Detail: B-column section*
Creation of baseline thermal simulation model

- Connector elements
- Heat bridges
- Adhesive lines
- Welding spot

Thermal simulation of a complete vehicle including manikins, S.Paulke et al. SIMVEC, 2014
Creation of baseline thermal simulation model

Shell element remeshing
Creation of baseline thermal simulation model

Remeshing with volume elements

Seals:
Creation of baseline thermal simulation model

Example of:
- Volume element meshing
- Contacts

Thermal simulation of a complete vehicle including manikins, S.Paulke et al. SIMVEC, 2014
Creation of baseline thermal simulation model

Mechanisms of heat transfer

- Reflection, transmission, absorption of wind screen
- Solar shortwave radiation
- Diffuse radiation
- Longwave radiation exchange with sky
- Convective exchange with surrounding air
- Conduction

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SIMVEC, 2014

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Creation of baseline thermal simulation model

Example:
Transmissivity (standard glass) dependency on wave length and incidence angle
Creation of baseline thermal simulation model

Climate chamber model (summer load case)

Sun (1000W/m²)
Parallel radiator

Climate chamber (54 lamps)
Creation of baseline thermal simulation model

Cabin air zonal modelling

each "airzone" has an average air temperature and humidity as degree of freedom

![Diagram showing cabin air zonal modelling with different zones labeled: Cabin air (top), Dash board, Engine space, Cabin air (bottom), Trunk. Each zone is color-coded and labeled accordingly.]
Validation of summer load case „Pull-Down“ - Baseline

Creation of baseline thermal simulation model
Creation of baseline thermal simulation model

Validation of summer load case „Pull-Down“ - Baseline

Solar roof panel powering passive ventilation, t<0

⇒ Reduction by 6-7°C

Cabin air average temp.
Creation of baseline thermal simulation model

Validation of summer load case
Solid part temperature, $t = t_{\text{max}}$ (Simulation)

$\Delta T$

$T_{\text{max}}$

$T_{\text{min}}$

FE Energy
Creation of baseline thermal simulation model

Baseline model statistics

**Number of FEs**
- # Shells: 2.1 million
- # Facets: 4.2 million
- # Solids: 1.1 million
- # 1D-Verbindungen: 0.2 million
- # DOF: 4.3 million

**Material data**
- # Properties: 2,600
- # Materials: 90

**Computation time**
- # 4 CPUs: 2-5h

**Model creation effort**
- Several months, including research of material parameters
Part 2:

Simplified simulation model
Simplified simulation model

Winter load case "Heat up"

Area correction factor \[ x = \frac{A}{A_{\text{Generator}}} \]

GeneratorModel (no area correction)
GeneratorModel (with area correction)
Baseline model

Cabin average air temperature

Time[sec]

GeneratorModel (THESEUS-FE)

Airzone 1
Airzone 2
Airzone 3
Airzone 4
Simplified simulation model

1D heat conduction modelling

Layer configuration:
1. 0.7 mm steel sheet \((c_1, \rho_1, \lambda_1)\)
2. 8.5 mm liner
3. 25 mm air
4. 9.4 mm canvas

Air layer:

\[
\begin{align*}
\frac{d}{dx} q_{\text{cond}}^n &= - \frac{T_{n-1}^n - T_{n+1}^n}{t^n} k_{\text{eff}}^n \\
 k_{\text{eff}} &= \underbrace{h_{\text{conv}} t_n}_{\text{convection}} + \frac{t^n \sigma}{1/\varepsilon^{n-1} + 1/\varepsilon^{n+1} - 1} \left[ (\bar{T}^{n-1} + \bar{T}^{n+1}) \left[ (\bar{T}^{n-1})^2 + (\bar{T}^{n+1})^2 \right] \right] \\
\bar{T} &\text{ in Kelvin}
\end{align*}
\]
Part 3

Concepts for zonal climatization
Concepts for zonal climatization

Winter load case "Heat up"

Zone 1+2: Driver + Passenger

Zone 3+4

Face outlets

$T_{env} = -7°C$

• Steady-state flow assumed
• CFD $\rightarrow$ Volume flow rates through zone borders
• Constant outlet temperature assumed
• Overall goal: raise temperature in driver zone to 24.7 °C after 10 min (corresponds roughly to PMV=0)

CFD: with OpenFOAM

Face outlets

Tenv = -7°C
Concepts for zonal climatization

Winter load case
Variants

Baseline:

Variant 1:

Variant 2: (assym.)

Variant 3: (assym.)

$T_{env} = -7^\circ C$
Concepts for zonal climatization

Winter load case

Variants

**Baseline:**
- Zone 1: Driver, 24.7°C
- Zone 2: Passenger, 24.7°C
- Zone 3: Rear, 20.2°C

Energy usage = 100%

**Variant 1:**
- Zone 2: Passenger, 24.7°C
- Zone 1: Driver, 24.7°C
- Zone 3: Rear, 13.1°C

Energy usage = 83%

**Variant 2:** asymmetric
- Zone 2: Passenger, 5.1°C
- Zone 1: Driver, 24.7°C
- Zone 3: Rear, 13.5°C

Energy usage = 73%

**Variant 3:** asymmetric
- Zone 2: Passenger, 11.3°C
- Zone 1: Driver, 24.7°C
- Zone 3: Rear, 16.7°C

Energy usage = 98%

$T_{env} = -7°C$
Concepts for zonal climatization

**Basis**

**Variant 1**

**Variant 2**

**Variant 3**
Part 4:

1. IR radiators and local thermal comfort
Winter load case
Variants with reduced outlet temperature

- Baseline without IR emitters
- Var. 1 with IR emitters above
- Var. 2 with IR emitters above and below
IR radiators and local thermal comfort

Coupled comfort simulations

- Data exchange with OpenFOAM via mapping

- Thermophysiology model: FIALA-FE
  - Heat conduction within body
  - Circulatory system, metabolism, shivering
  - Contact heat flow, clothing, respiration, transpiration, sweating
    (incl. humidity exchange with OpenFOAM)

- Thermal comfort evaluation for human model FIALA-FE: PMV, DTS, Teq, ISO-14505-2, Zhang

- 3D heat conduction in solids with THESEUS-FE

- 3D radiation thermal and solar in THESEUS-FE

\[
\dot{Q}_{\text{convection}} = A \cdot h \cdot (T_{\text{fluid}} - T_{\text{wall}})
\]
**IR radiators and local thermal comfort**

**Coupled comfort simulations**

*What data is exchanged during co-simulation?*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Source</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall temperature $T_{\text{wall}}$</td>
<td>°C</td>
<td>THESEUS-FE</td>
<td>OpenFOAM</td>
</tr>
<tr>
<td>Local convective coefficient of heat transfer $h$</td>
<td>W/(m²K)</td>
<td>OpenFOAM</td>
<td>THESEUS-FE</td>
</tr>
<tr>
<td>Adjacent fluid temperature $T_{\text{fluid}}$</td>
<td>°C</td>
<td>OpenFOAM</td>
<td>THESEUS-FE</td>
</tr>
<tr>
<td>Current time increment $\Delta t$</td>
<td>S</td>
<td>THESEUS-FE</td>
<td>OpenFOAM</td>
</tr>
<tr>
<td>Rate of water vapor generation $J$</td>
<td>kg/(m²s)</td>
<td>THESEUS-FE</td>
<td>OpenFOAM</td>
</tr>
<tr>
<td>Mass fraction of water vapor $Y_{\text{H}_2\text{O}}$</td>
<td>-</td>
<td>OpenFOAM</td>
<td>THESEUS-FE</td>
</tr>
<tr>
<td>Air pressure $p$</td>
<td>Pa</td>
<td>OpenFOAM</td>
<td>THESEUS-FE</td>
</tr>
<tr>
<td>Avg. inlet temperature $T_{\text{in}}$</td>
<td>°C</td>
<td>AC model</td>
<td>OpenFOAM</td>
</tr>
<tr>
<td>Avg. water vapor fraction $X_{\text{H}_2\text{O},\text{in}}$</td>
<td>-</td>
<td>AC model</td>
<td>OpenFOAM</td>
</tr>
<tr>
<td>Avg. outlet temperature $T_{\text{out}}$</td>
<td>°C</td>
<td>OpenFOAM</td>
<td>AC model</td>
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<tr>
<td>Avg. water vapor fraction $X_{\text{H}_2\text{O},\text{out}}$</td>
<td>-</td>
<td>OpenFOAM</td>
<td>AC model</td>
</tr>
<tr>
<td>PMV (=global comfort index)</td>
<td>-</td>
<td>THESEUS-FE</td>
<td>AC model</td>
</tr>
</tbody>
</table>
Part 5:

Validation of coupled cabin simulation

OpenFOAM ↔ THESEUS-FE
Validation of coupled cabin simulation

Validation summer load case ("pull-down")
Validation of coupled cabin simulation

Validation summer load case

VDA
Head front

VDA
Head rear

VDA head front

VDA front rear

Lüfterstufe 7, Temperaturvergleich

Lokale Lufttemperatur

0 500 1000 1500 2000 2500 3000 3500

VDA_Kopfhi (MES)
VDA_Kopfvo (MES)
VDA_Kopfhi (SIM)
VDA_Kopfvo (SIM)