
Contents

Nomenclature **15**

1. Industrial motivation **19**

- 1.1. Digital development process 19
- 1.2. Electronic equipment in a passenger car, heat transfer mechanisms..... 21
 - 1.2.1. Heat sources 21
 - 1.2.2. Heat transport by convection 21
 - 1.2.3. Heat transport by conduction 22
 - 1.2.4. Heat transport by radiation..... 23
- 1.3. Use cases for the electronics temperature..... 23
- 1.4. Target electronic devices in the development process 25
- 1.5. Thermal management of electronics in the digital development process..... 26

2. State of literature **27**

- 2.1. Numerical methods for the thermal management of a passenger car..... 28
 - 2.1.1. Development of coupling simulation methods 28
 - 2.1.2. Numerical methods used in the DPT process at Daimler AG 29
- 2.2. Heat transfer mechanisms in elementary electronic systems 29
 - 2.2.1. Conduction at junction and case levels 30
 - 2.2.2. Natural convection in electronic cavities 31
 - 2.2.3. Forced convection in electronic channels 33
 - 2.2.4. Mixed convection in electronic channels..... 33
- 2.3. Thermal management of electronic systems 35
 - 2.3.1. Conjugate convective and conductive heat transfer modes 35
 - 2.3.2. Convective, conductive and radiation heat transfer modes 35
- 2.4. Partial conclusions 37
- 2.5. Aim and challenge of the project..... 38

3. Development of a numerical method for the thermal management of electronics in passenger cars	41
3.1. Characteristic time of temperature propagation	41
3.1.1. Transport by convection	42
3.1.2. Transport by conduction	45
3.1.3. Transport by radiation.....	46
3.1.4. Partial conclusions	46
3.2. Mathematical model for the prediction of the electronic temperature in the development process.....	47
3.2.1. Governing equations	47
3.2.2. Time-dependent coupled heat transfer problem	50
3.2.3. Resolution of the coupled problem in the development process	51
3.3. Solid solvers	52
3.3.1. Mesh generation for RadTherm and PERMAS computations.....	52
3.3.2. Thermal analysis software RadTherm	52
3.3.3. Finite element code PERMAS and radiation code POSRAD.....	53
3.4. Flow solver STAR-CD	55
3.4.1. Mesh generation.....	55
3.4.2. Turbulence modeling	55
3.4.3. Convective heat transfer at the interface.....	56
3.4.4. Discretisation and solution algorithm	57
3.5. Modeling of the flow in electronic enclosures	58
3.5.1. Buoyancy-driven flows	59
3.5.2. Forced convective flows	59
3.6. Coupling codes strategies	63
3.6.1. Data transfer at the fluid-solid interface	63
3.6.2. Mesh mapping for matching boundary conditions	64
3.6.3. Transient coupling of heat transfer modes.....	64
3.7. Experimental methods used for numerical validation	68
3.7.1. Laboratory conditions	68
3.7.2. Real environment in the vehicle	71
3.8. Partial conclusions	72

4. Validation and accuracy of the convective heat transfer prediction	73
4.1. Buoyancy-driven flows.....	73
4.1.1. Structure of the flow, rectangular box	75
4.1.2. Heat transfer rate, cubical cavity	79
4.1.3. Partial conclusions	85
4.2. Forced convective flows	86
4.2.1. MRF simulation	86
4.2.2. Rotational body force simulation.....	89
4.2.3. Partial conclusions	91
4.3. Outlet grills of the TV-tuner	92
4.3.1. Grill modeling in the test-rig.....	93
4.3.2. TV-tuner, outlet grills	96
4.3.3. TV-tuner, porous resistance elements.....	100
4.3.4. Partial conclusions	104
5. Validation of the co-simulation strategies on electronic systems in a vehicle	105
5.1. Battery in the spare-wheel cavity	105
5.1.1. Critical parts and thermal requirements.....	105
5.1.2. Use cases and experimental investigations	106
5.1.3. Numerical models	108
5.1.4. Model validation of the battery in the spare wheel cavity	111
5.1.5. Validation of the coupling strategy, case of summer.....	115
5.1.6. Determination of a critical use case of summer.....	118
5.1.7. Partial conclusions	119
5.2. Sound amplifier in a cavity under the passenger's feet	120
5.2.1. Thermal requirements and heat transfer mechanisms.....	120
5.2.2. Use case and experimental results	122
5.2.3. Numerical models	123
5.2.4. Model validation of the sound amplifier in the feet compartment, fan switched off.....	127
5.2.5. Validation of the coupling strategy, fan switched off.....	130
5.2.6. Partial conclusions	132
6. Discussion and perspectives	133
Bibliography	135

Appendix	149
A.1. Characteristic numbers	149
A.2. Thermal analysis with the FEM code PERMAS	150
A.3. Experimental methods	151
A.3.1. Fan test-rig	151
A.3.2. Perforated plate performance curve	152
A.3.3. K-type thermocouples	153
A.4. Buoyancy-driven flows.....	154
A.4.1. Rectangular box	154
A.4.2. Horizontal cubical cavity	156
A.5. Forced convective flows	162
A.5.1. Electronic fans considered	162
A.5.2. Turbulence modeling and mesh refinement study	162
A.6. Outlet grills, TV-tuner	165
A.6.1. Geometric parameters	165
A.6.2. Grill modeling	166
A.6.3. TV-tuner, outlet grills	168
A.6.4. Upper grill of the TV-tuner in the test-rig	171
A.6.5. TV-tuner, 2D and 3D porous elements	172
A.7. Battery in the spare-wheel cavity	174
A.7.1. Experimental set-up and results	174
A.7.2. Numerical model.....	176
A.7.3. Validation of the numerical model	177
A.7.4. Validation of the coupling strategy.....	178
A.7.5. Critical use case of summer	179
A.8. Sound amplifier in a cavity under the passenger's feet	180
A.8.1. Measurements of the thermal resistances and capacitances from the power ICs in the main heat path.....	180
A.8.2. Experimental set-up in the vehicle and results	182
A.8.3. Numerical model.....	183
A.8.4. Validation of the numerical model	185