Feasibility Study for Optimisation in Thermal Management of Hybrid Vehicles

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Sokrates

Dedication

I dedicated this thesis to my family, who always supported my plans and studies. I want to thank my friends for inspiration and exchange. I want to give special thanks to Prof. Raimund Almbauer and Prof. Stefan Hausberger for perceptive supervision, to Dr. Gregor Gregorcic for profound support and to Dipl.Ing.(FH) Gernot Herschold-Pießnig and his team for persistent advising. Finally I want to thank the company qpunkt GmbH for making this thesis possible.

Abstract

This investigation explores possibilities of cooling system design optimisation for hybrid vehicles. Difficulties related to thermal management of hybrid vehicles increase due to a high number of components in the propulsion system. Different operating temperatures and the decline of heat sources, due to efficiency improvements, demand an integrated cooling system design that enables specific heat distribution as well as saving in construction space.

At the beginning of this thesis an analysis of the components applied in the state of the art hybrid vehicles explores the temperature and amount of heat transferred in the cooling system. To cope with the complex interdependencies while driving the set up of a compound of usecases enables a description of the components' thermal behavior in the second step. The utilisation of synergy effects is investigated.

Subsequently different cooling systems architectures are designed executing an introduced concept development procedure. After the evaluation of the particular layouts, two designs are investigated particularly by the simulation of a sedan hybrid vehicle using the 1-D simulation software KULI ®. A steady-state maximum speed drive case shows deficiencies between concepts and highlights benefits of optimisation of the thermal management paradigm.

A final assessment focuses on thermodynamic feasibility and energy consumption. Construction space allocation and system complexity are the key factors determining the development of integrated cooling system design.

Kurzfassung

Die vorliegende Arbeit befasst sich mit der Optimierung des Kühlsystems in Hybridfahrzeugen. Die zusätzlichen Komponenten, die in das Antriebssystem eingebunden werden müssen, stellen das thermische Management vor neue Herausforderungen. Die Unterschiede bei den Betriebstemperaturen und der fortschreitende Mangel an Wärmequellen, verursacht vor allem durch Effizienzsteigerungen der Verbrennungskraftmaschine, erfordert neue Ansätze beim Entwurf eines integrierten Kühlsystems.

Zu Beginn der Arbeit werden in einer Komponentenanalyse die Betriebstemperaturen und auftretende Wärmemengen von Hybridfahrzeuge nach Stand der Technik aufgezeigt. Die komplexen Zusammenhänge zwischen diesen Komponenten werden durch die Einführung vereinfachter Betriebsfälle überschaubar gemacht. Das thermische Verhalten der Komponenten wird beschrieben und mögliche Synergieeffekte werden abgeleitet, bei denen Wrmequellen mit Wrmesenken verbunden werden sollen. Zustzlich soll Bauraum durch eine reduzierte Systemarchitektur zurückgewonnen und gezielte Wärmeverteilung durch geeignete Verschaltungen ermöglicht werden.

Die erarbeitete Konzeptentwicklungsprozedur unterstützt den Entwurf neuer Kühlsystemkonzepte unter Berücksichtigung thermodynamischer, energetischer und produktionstechnischer Einschränkungen. Nach ersten Evaluierungen werden zwei Kühlsystementwrfe fr ein Hybridfahrzeug simuliert. Der stationäre Hochgeschwindigkeitsfall mit höchster thermischer Last wird mithilfe der 1-D Simulationssoftware KULI ® dargestellt.

Eine abschlieende Bewertung ermittelt die thermodynamische Machbarkeit, den Energieverbrauch, die Bauraumbelegung und die Systemkomplexität als die Haupteinflussfaktoren für die Entwicklung neuer Kühlsystemarchitekturen.

Contents

Nomenclature

Latin Symbols

a_{Veh}	=	Vehicle acceleration	$[m/s^2]$
A	=	Area	$[m]$
A_{Veh}	=	Projective vehicle area	$[m^2]$
b	=	Breadth	$[m]$
c_p	=	Specific heat capacity	$[J/kgK]$
C_d	=	Drag coefficient	$[-]$
C_{rr}	=	Coefficient of rolling resistance	$[-]$
cp	=	Pressure coefficient	$[-]$
d	=	Diameter	$[m]$
ETD	=	Entering temperature difference	$[K]$
F_a	=	Force of acceleration	$[N]$
F_{asc}	=	Force of ascent	$[N]$
F_R	=	Force of driving resistance	$[N]$
g	=	Gravitational acceleration	$[m/s^2]$
h	=	Specific enthalpy	$[J/kg]$
k	=	Overall heat transfer coefficient	$[W/m^2K]$
L_{char}	=	Characteristic length	$[m]$
$\dot{m}$	=	Mass flow	$[kg/s]$
m_{Veh}	=	Vehicle mass	$[kg]$
Nu	=	Nusselt number	$[-]$
p	=	Pressure	$[Pa]$
P_{Wheel}	=	Required wheel power	$[W]$
Pr	=	Prandtl number	$[-]$
q	=	Heat flux density	$[W/m^2]$
q_0	=	Specific evaporator performance	$[J/kg]$
q_c	=	Specific condenser performance	$[J/kg]$
Q	=	Heat flow	$[W]$

Re	=	Reynolds number	$[-]$
t	=	Temperature	$[^\circ\mathrm{C}]$
T	=	Temperature	$[K]$
T_F	=	Fluid temperature	$[K]$
T_I	=	Temperature of the inner medium	$[K]$
T_O	=	Temperature of the outer medium	$[K]$
T_W	=	Wall temperature	$[K]$
v	=	Velocity	$[m/s]$
$\dot{V}$	=	Volume flow	$[m^3/s]$
w	=	Specific compressor performance	$[J/kg]$
W	=	Thermal capacity stream	$[W/K]$
W_I	=	Inner medium thermal capacity stream	$[W/K]$
W_K	=	Minimum of thermal capacity streams	$[W/K]$
W_O	=	Outer medium thermal capacity stream	$[W/K]$
z	=	Height	$[m]$

Greek Symbols

α	=	heat transfer coefficient	$[W/m^2K]$
δ	=	Diameter	$[m]$
ε	=	Emissivity	$[-]$
λ	=	Coefficient of thermal conductivity	$[W/mK]$
∇	=	Nabla operator	$[-]$
ν	=	Kinematic viscosity	$[m^2/s]$
ξ	=	Pressure Loss coefficient	$[-]$
ρ	=	Density	$[kg/m^3]$
σ	=	Stefan-Boltzmann constant	$[W/m^2K^4]$
Φ	=	Operation characteristics coefficient	$[-]$

Acronyms and Abbreviations

AH	:	Auxiliary heater
Batt.	:	Battery
BAT	:	Battery
Cab.	:	Cabin
C.Air	:	Charge air
CAT	:	Catalyser
C.Eng.	:	Internal combustion engine
Cool.	:	Coolant
CO	:	Condenser (Refrigerant circuit)
COND	:	Condenser (Refrigerant circuit)
EG	:	Exhaust gas cooling
EM	:	Electric Motor
E.Mot	:	Electric motor
EV	:	Evaporator (Refrigerant circuit)
EVAP	:	Evaporator (Refrigerant circuit)
Ex.G.	:	Exhaust gas cooling
HX	:	Heat exchanger
HEAT	:	Heater
HV-PTC	:	High voltage positive temp. coefficient heater
ICE	:	Internal combustion engine
INT	:	Intercooler
LTC	:	Low temperature radiator
NEUT	:	Neutral component behaviour
OEM	:	Original Equipment Manufacturer
PE	:	Power electronics
P.Elec.	:	Power electronics
Precond.	:	Preconditioning
Ref.	:	Refrigerant circuit
SINK	:	Heat sink
SOUR	:	Heat source

TC	:	Turbo charger
Temp.	:	Temperature
TM	:	Transmission
TRANS	:	Transmission
Transm.	:	Transmission
UC	:	Usecase

Chapter 1

Hybrid Vehicles

1.1 Introduction

THE hybrid vehicle is the response of the automotive industry to tdemand of society to make personal transportation less polluting and more efficient. The main concept is to substitute parts of the the internal combustion engine with electric motor in order to enhance efficiency, driving performance and to reduce the problem of waste gases. Unfortunately the electrification brings up number of difficulties. The energy density of battery systems can not reachthe energy density of liquid fuels. This sets limitations to driving range, vehicle costs and cabin climatisation. To meet the customers' high comfort demands the automotive industry tries to combine advantages of the internal combustion engine concept and the electrical concept in a hybrid vehicle. Thus the number of the required components increases and raises further difficulties in construction space management, component harmonisation and cooling system design.

An integrated thermal management of those components, which highly differ in thermal requirements, is one of the great technical challenges the cooling system of a hybrid vehicle faces. This thesis investigates technical capabilities in optimisation of hybrid vehicles' cooling systems regarding reduction of hardware complexity, energy consumption and utilisation of synergy effects. In the following section the components of hybrid vehicles are described and the technical challenges of the cooling system are analysed.

1.2 Types of Hybrid Vehicles

The combination of combustion and electrical propulsion in hybrid vehicles can be accomplished in different ways. The diverse types on the market can be categorised by their kind of propulsion linkage [1].

1.2.1 Serial Hybrid

The serial hybrid is purely electric driven. The internal combustion engine operates as a power generator without any direct wheel connection. Therefore rotational speed of the internal combustion engine can be chosen in the most effective range. On the other hand transformation losses from combustion power to electrical power and again from electrical power to wheel power lower the efficiency gains.

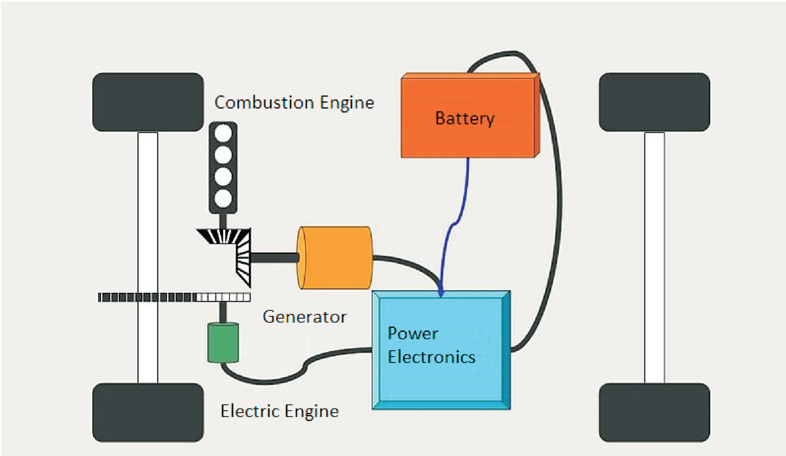

Figure 1.1: Serial Hybrid

1.2.2 Parallel Hybrid

The parallel hybrid vehicle is electrically and combustionally propelled. The advantage of direct conjunction from internal combustion engine to wheel is combined with the disadvantage of a permanent drag torque of the electric machinery.

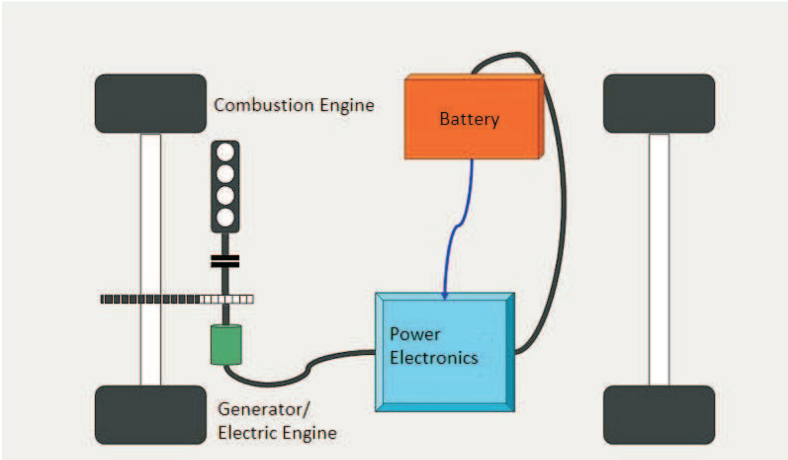

Figure 1.2: Parallel Hybrid

1.2.3 Power Split Hybrid

The power split of electric and combustion propulsion is realised by clutches or gearboxes. This allows a mixture of propulsion power adjustable to different operational requirements.

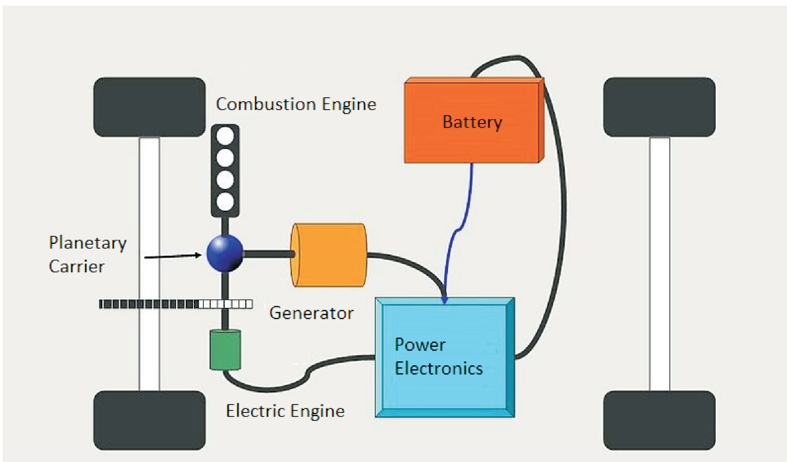

Figure 1.3: Power Split Hybrid

1.3 Component Analysis

In the following section the components which have to be integrated in the cooling system are analysed concerning power range, temperature level and required volume flow of the coolant. Disregarding specific components the values are experienced data from current hybrid vehicles.

1.3.1 Passenger Compartment

In the temperate zone the climatisation of the passenger compartment requires heating in winter cases and cooling in summer cases. To guarantee the passengers' comfort and safety the air qualities like temperature and vapour content in the cabin must not exceed certain limits that vary depending on environmental influences [2]. Air conditioning in summer cases is realised by the use of a refrigerant cycle. Depending on the size of the vehicle the performance range of the evaporator is between 3 and 5 kW. In winter cases the needed heating performance ranges between 6 and 10 kW, which can be problematic for hybrid vehicles with small sized combustion engines and accordingly low power dissipation, which is used for cabin heating.

1.3.2 Internal Combustion Engine

Current hybrid vehicles strongly vary in size and performance [3]. The power of the internal combustion engine ranges from 50 up to 300 kW. Roughly estimated the same amount of power is lost in heat removal as it is lost by exhaust gases. The cooling system receives a part of the heat removal by coolant flow through the engine and, if applied, through an exhaust gas cooling. The coolant volume flow varies form 20 to 300 l/min. The temperature level of the coolant after the engine outlet should be around 90 °C. The ideal temperature of the internal combustion engine is of significant matter to efficient operation. Therefore warmup after cold start should be achieved as quickly as possible. Referring to very high thermal mass in comparison to the other components the internal combustion engine can be seen as heat sink without any suitable heat sources in this case. In normal operation the internal combustion engine represents the most important heat source for the thermal management.

1.3.3 Transmission

The efficiency of the transmission is strongly depending on the oil temperature, which should range around 120 °C. Power dissipation brings up to 7 kW of heat into the cooling system. Like the combustion engine a quick warmup is important to keep losses low.

1.3.4 Exhaust Gases

As mentioned in section 1.3.2 the amount of heat lost to ambiance ranges from 50 to 300 kW. A heat recovery is not yet state of the art, but in development. The degree of recovery can be assumed low with around 10%.

1.3.5 Charge Air

Turbocharged combustion engines are state of the art to increase efficiency and optimise power characteristics. After compression the charge air needs to be cooled down in order to achieve higher density for more oxygen brought to the combustion chamber. Depending on the engine size the heat brought into the cooling system can reach up to 14 kW respecting a temperature level of 80 °C before engine inlet.

1.3.6 Electric Motor

Current configurations of hybrid vehicles operate with electric power ranging from 10 to 165 kW. Due to the high degree of efficiency (60% - 90%), heat brought into the cooling system can vary from 1 to 66 kW. The component temperature can rise up to 70 °C, but high temperatures trigger negative effects on durability as figure 1.4 shows.

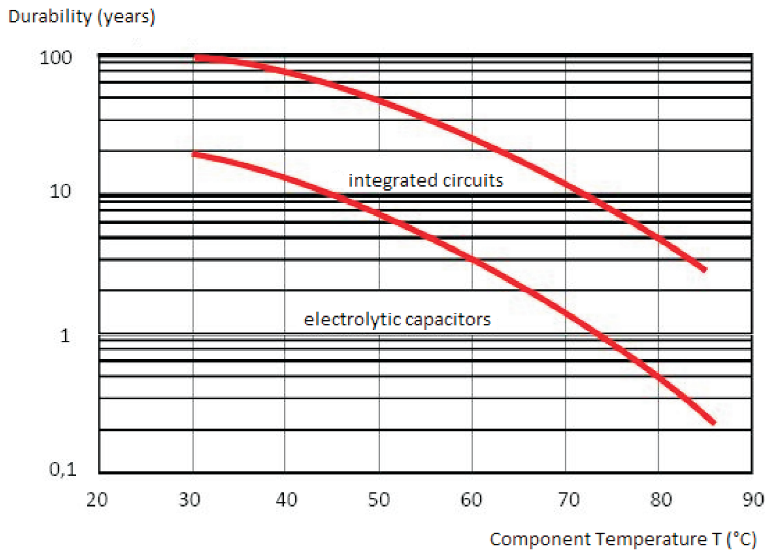

Figure 1.4: Durability of electric components depending on operating temperature [mbi-gmbh, 2012]

1.3.7 Power Electronics

Based on the power consumption of the electric motor ranging from 10 to 165 kW the thermal power dissipation can be expected with 10% to 40% of the transformed power (1 to 66 kW). As said in section 1.3.6 high component temperatures cause significant damages lowering durability. Therefore coolant temperature should not exceed 65 °C respectively be kept as low as possible.

1.3.8 Battery

The battery is highly susceptible to temperature. In the temperate zone temperatures often decrease below 0 °C which cuts down power output remarkably. Temperatures above 40 °C should be avoided to prevent damages in battery cell structure. The optimal operating temperature ranges between 20 °C and 30 °C. Under these conditions power dissipation can be assumed below 5% due to high efficiency.

1.3.9 Auxiliary Heater

To achieve satisfying air conditions inside the passenger compartment and acceptable battery temperatures hybrid vehicles need auxiliary heating in case of low ambient temperatures and absence of other heat sources. Companies' sales strategies often prohibit applications of fuel heaters what makes electrical heating necessary although enormous driving range losses are entailed. The auxiliary heating can bring up to 2 kW into the cooling system.

1.3.10 Overview

The quoted values represent reference values that highly differ in driving operation and display a series of vehicle configurations shown in [3]. Furthermore the overall load of the cooling system is depending on the driving situation and has not to be assumed as high as the sum of all maximum amounts of heat brought into the cooling system.

Component	Heat to Cool.	Cool. Temp.	Coolant Vol. Flow
ICE	25 - 150 kW	90 °C	20 - 300 l/min
Transm	<7 kW	120 °C	5 - 50 l/min
Ex.G.	<30 kW	140 °C	5 - 50 l/min
C.Air	<14 kW	80 °C	20 l/min
E.Mot.	<70 kW	70 °C	20 l/min
P.Elec.	<70 kW	65 °C	20 l/min
Battery	<3 kW	10 °C	20 l/min
AH	<2 kW	100 °C	20 l/min
EVAP	<5 kW	<20 °C	<200 kg/h

Table 1.1: Component overview

1.4 Technical Challenges in the Cooling System

The cooling system of a hybrid vehicle faces different problems:

I. In the temperate zone heating demand in winter cases is harder to satisfy with increasing electrification of the vehicle, because the power dissipation of the internal combustion engine is no more sufficient. Therefore utilisation of any kind of heat sources shall be investigated to provide the following issues:

- comfort and safety of the passengers
- optimal operating conditions for sensitive components
- reduction of energy consumption
- reduction of exhaust gas emissions

II. The utilisation of heat sources within the hybrid vehicle requires a cooling system design that can distribute heat from where it is produced to where it is needed.

III. The analysis of the applied components shows significant differences in the cooling system requirements. Apart from the different amounts of power dissipation the varying operating temperatures as shown in figure 1.5 call for distinct technical solutions in the cooling system.

IV. The coolant supply for every single component by individual heat exchangers has to be avoided for several reasons:

- Costs: Production costs rise with additional components.
- Construction space: Additional components occupy construction space, not only the heat exchangers themselves but the piping system as well.
- Weight: The weight of the vehicle increases which has direct influence to energy consumption.
- Pumps: Multiple cooling circuits require several coolant pumps, which again increase energy consumption, weight and construction space allocation.

As shown in figure 1.5 some components would match in operating temperature what allows the introduction of an integrated cooling system which pools suitable components to keep the number of heat exchangers and piping effort low.

V. Since ambient temperature exceed the operating temperature of the cabin and the battery in summer cases the use of a refrigerant circuit is inevitable. The optimal inclusion in the vehicles' cooling system is of significant importance.

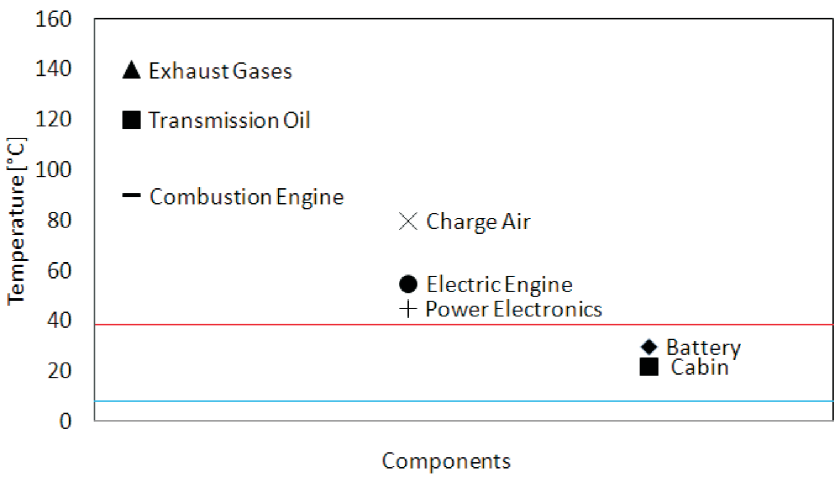

Figure 1.5: Operating Temperatures Overview

Chapter 2

State of the Art

COOLING system solutions of current hybrid vehicles are shown in the following section pointing out that the technical challenges discussed in section 1.4 are still not solved adequately. Subsequently the thermodynamic basics of heat transfer and heat removal are explained.

2.1 Concept 1

The parallel hybrid weighs around 2.300 kg. The combustion engine provides around 150 kW, the electric engine around 60 kW. The battery contains 16 kWh. As seen in figure 2.1 the cooling system is realised with four heat exchangers and one chiller (apart from the inevitable heatexchangers used for cabin climatisation).

BAT	Battery	ICE	Internal combustion engine
COND	Condenser	INT	Intercooler
CAT	Catalyser	LTC	Low temp. cooler
EM	Electric motor	PE	Power electronics
EVAP	Evaporator	RAD	Radiator
EG	Exhaust gases	TC	Turbo charger
HX	Heat exchanger	TRANS	Transmission

Table 2.1: Component abbrevaiations

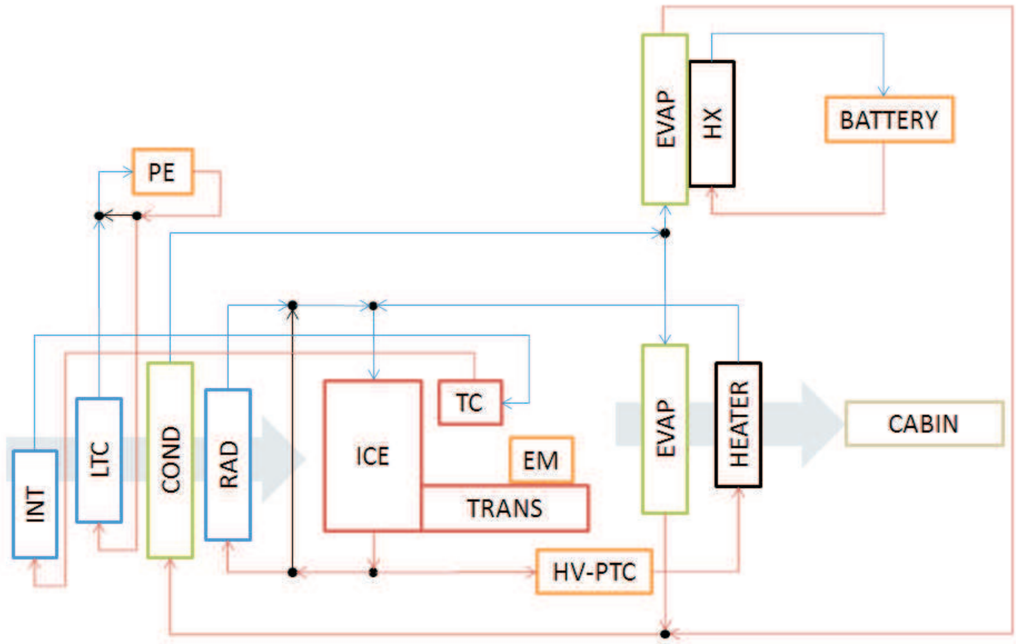

Figure 2.1: Concept 1 Layout

2.2 Concept 2

The serial hybrid concept weighs around 1.200 kg, the electric engine produces 45 kW of power, the combustion engine operates as a range extender and provides around 25 kW. The battery contains 11 kWh. The cooling system applies five heat exchangers and two chillers.

2.3 Concept 3

The mild hybrid vehicle weighs around 2.300 kg, the combustion engine supplies around 250 kW, the electric engine produces 35 kW, the battery contains 2 kWh. Five heat exchangers and one chiller represent the cooling system.

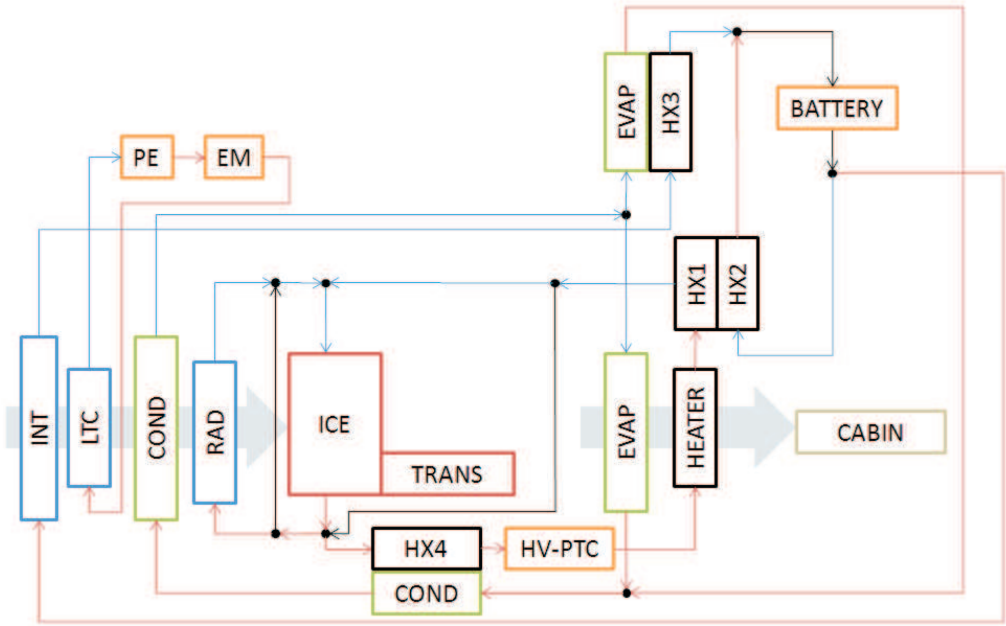

Figure 2.2: Concept 2 Layout

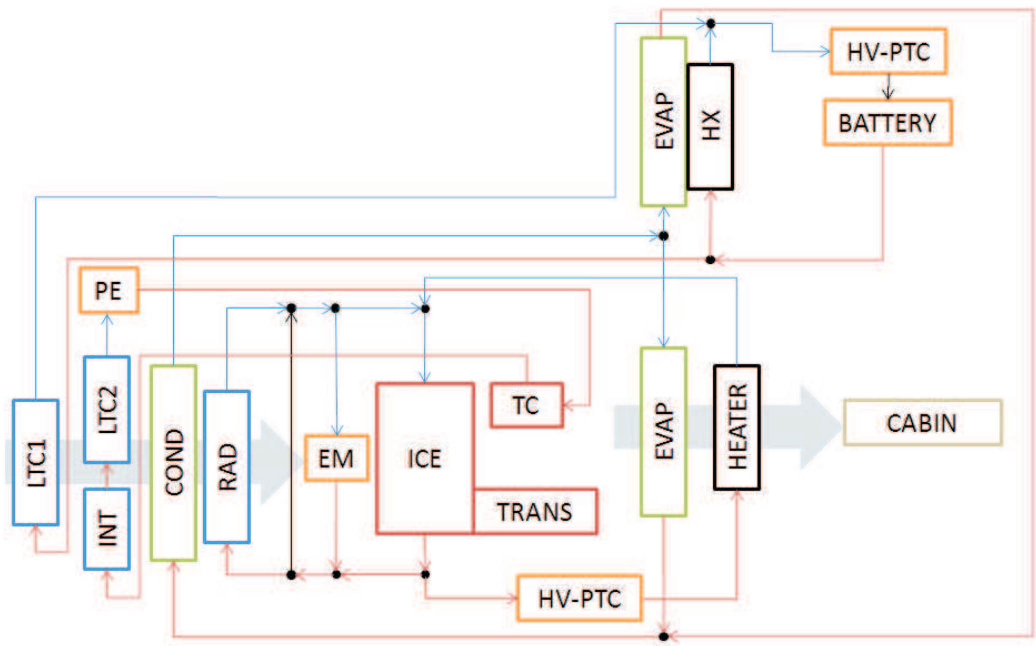

Figure 2.3: Concept 3 Layout

2.4 Lexus LS 600 h

This vehicle weighs around 2.300 kg, has an 290 kW combustion engine and an 165 kW electric engine. The battery contains 20 kWh of electric energy. Three heat exchangers build the cooling system applying an extra air cooling for rear passenger compartment and the battery.

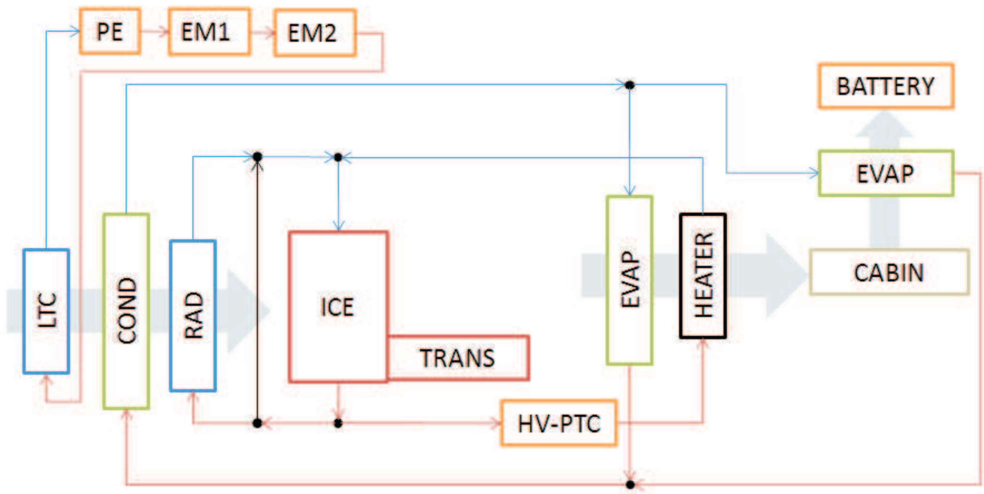

Figure 2.4: Concept Lexus LS 600 h

The state of the art shows that the concepts for a hybrid vehicle cooling system still do not solve the problems described in section 1.4 in a satisfying and optimal way. Neither the complexity level is kept low by the vast number of heat exchangers nor the cooling system design does support heat shifts within the components.

2.5 Thermodynamics

To describe the processes within the cooling system the determining thermodynamic principles are discussed in the following section. Generally heat transfer is caused by a temperature difference between two involved media. The transfer can happen in three ways:

I. Thermal Conduction: Transfer of thermal energy according to Fourier's law:

$$\vec{q} = -\lambda \vec{\nabla} T \tag{2.1}$$

II. Thermal Convection: Transfer of thermal energy according to Newton's law:

$$q = \alpha (T_W - T_F) \tag{2.2}$$

The heat transfer trough a wall can be calculated by:

$$Q = k \cdot A \cdot (T_1 - T_2) \tag{2.3}$$

where k is the heat transfer coefficient for a multilayer plane wall.

$$k = \frac{1}{\frac{1}{\alpha_1} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}} \tag{2.4}$$

III. Thermal Radiation: Transfer of thermal energy according to the Stefan-Boltzmann law:

$$Q = \varepsilon \cdot \sigma \cdot A \cdot T^4 \tag{2.5}$$

Within the cooling system of a hybrid vehicle all kinds of heat transfer occur whereas the partitioning can hardly be quantified. To calculate the exact heat transfer taking place within driving operation the application of numerical simulation (1-D and CFD) software in combination with measurement evaluation is necessary.

2.5.1 Heat Exchanger

A heat exchanger is a device for the transfer of thermal energy from one medium to another medium. The aggregation state can be whether gaseous, liquid or toggle between these states as it does in an evaporator or condenser described in section 2.5.3. As shown in figure 2.5 the two mass flows enter the heat exchanger with certain temperatures (T') and specific enthalpies (h').

After the heat transfer along the surface (A) determined by the heat transfer coefficient (k) the mediums leave with altered temperature (T") and specific enthalpy (h").

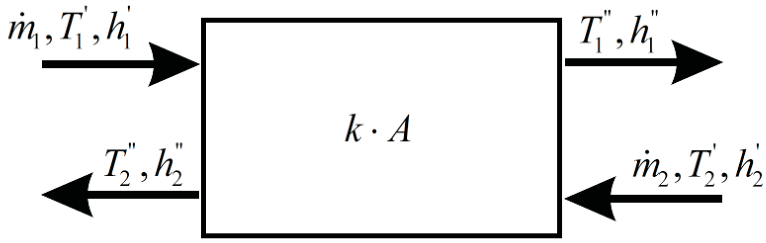

Figure 2.5: Heat Exchanger

The figures of the cooling system designs show this component separated with indication "HXy" to entitle the coolant perfusion.

2.5.1.1 Radiator: Fluid-gas Heat Exchanger

In automotive industry radiators are applied for cooling of components producing waste heat above ambient temperature level (internal combustion engine, transmission, exhaust gases, charge air, electric motor, power electronics). The radiators are mostly located in the front of the car to get as much air through as possible. Thereby the assembly of the heat exchangers is very important. The condenser of the refrigerant circuit is located in the first place as the waste heat temperature level is the lowest. Afterwards the radiator of the combustion engine and the transmission is disposed.

2.5.1.2 Chiller: Fluid-fluid Heat Exchanger with Phase Transition

A chiller is a special heat exchanger device for heat removal of a fluid by utilisation of a refrigerant circuit. It is implemented as a fluid-fluid heat exchanger whereas the refrigerant changes phase from liquid to gaseous absorbing additional heat. It is possible to use this device in heat pumpe mode operating with inverted circuit direction and transferring heat to the coolant by condensation. The figures of the cooling system designs show this device as a heat exchanger where the coolant flows through the "HX" whereas the other part is indicated by the refrigerant phase change.

2.5.2 Mixing Chamber

In the adiabatic and isobaric mixing chamber two input enthalpy flows are brought together and mixed completely. The determining equation provides information about the mixture.

$$\dot{m}_m \cdot h_m = \dot{m}_1 \cdot h_1 + \dot{m}_2 \cdot h_2 \tag{2.6}$$

$$\dot{m}_m = \dot{m}_1 + \dot{m}_2 \tag{2.7}$$

2.5.3 Refrigeration Cycle

The closed refrigeration cycle uses the beneficial properties of the refrigerant to absorb heat at low temperatures by evaporation. This is achieved by the use of a heat exchanger (evaporator) where the refrigerant inside absorbes heat from the outer medium by phase transition to gaseous state. Subsequently the refrigerant is compressed thus brought to a higher pressure and temperature level. Afterwards the refrigerant can release the absorbed heat plus the compression work added by the compressor by flowing through the condenser and changing aggregate state back to liquid again. Now the positive temperatur gradient to ambient temperature allows heat removal. The phase transition to liquid supports the heat transfer to the ambience. After the expansion valve decreasing the pressure the cycle starts again by changing phase to gaseous and absorbing heat. This principle allows to cool down the involved mediums below ambient temperature. Nevertheless the use of the refrigerant cycle should be minimised due to significant energy consumption for heat removal.

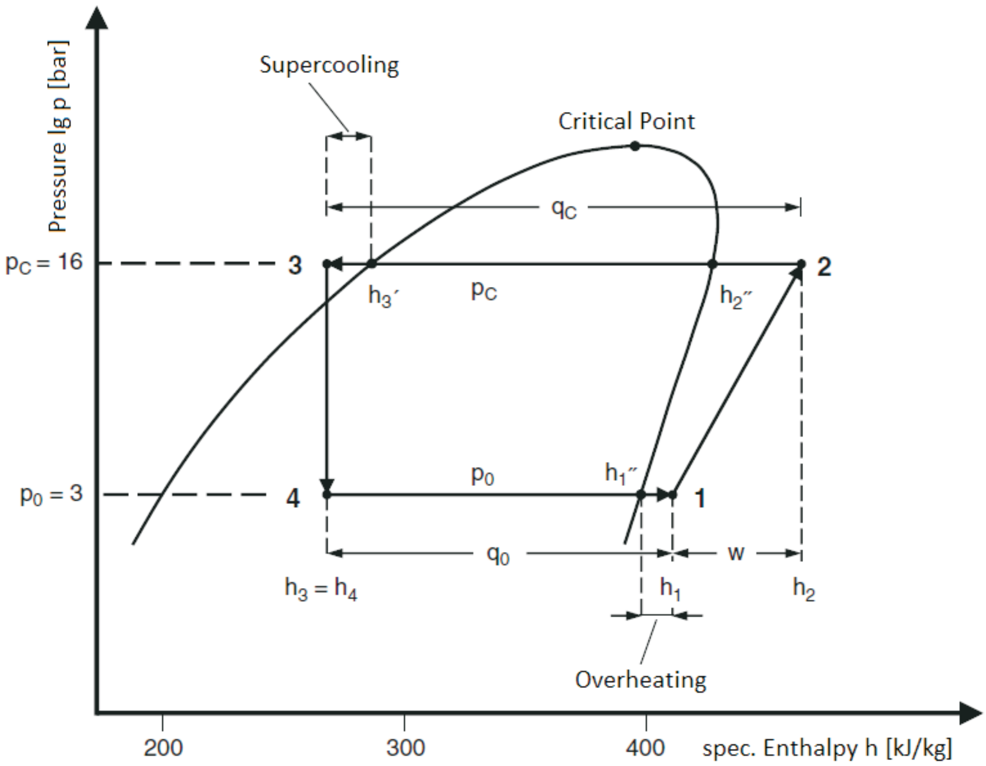

Figure 2.6: p,h-Diagram of a Refrigerant Circuit [Großmann, 2010]

Chapter 3

Concept Development

To find out how the cooling system of a hybrid vehicle can be opitmised the first step has been a set up of usecases, which display the different driving operations and the determining factors to the components' behaviour in terms of heating and cooling demand. Afterwards the technical boundary conditions have been established and a development procedure for new design concepts has been introduced.

3.1 Usecases

Throughout the product life cycle the hybrid vehicle experiences countless operating conditions depending on a multitude of factors. Besides speed, inclination, drivers' behaviour, control strategy etc. another main influence is the ambient temperature, determining demands of heating or cooling. To find out how the cooling system components behave in changing driving conditions certain simplifications have brought up a series of usecases to display every different kind of cooling or heating demand. These simplifications concern the:

- ambient temperature
- propulsion mode
- driving operation
- special events

3.1.1 Ambient Temperature

Although temperatures in the tempered zone strongly vary within a year the requirements to the cooling system can be derived from two simplified cases:

3.1.1.1 Summer Case

The summer case represents conditions where the ambient temperature exceeds operating temperatures of the cabin and the battery. No matter how much the ambient temperature outreaches this level, the cabin and the battery demand cooling. Contrary to the other components, which can be cooled by a coolant circuit, these elements can only be conditioned by a refrigerant circuit transferring the heat to a higher temperatur level.

3.1.1.2 Winter Case

In opposite to the summer case the ambient temperature falls below optimal conditioning of battery and cabin in winter case. As the thermal losses of the cabin caused by missing isolation outgo thermal gains by passengers and technical equipment, enough heat has to be supplied to keep cabin temperature constant. Though the battery is often better insulated the power dissipation may not be suficient to reach operating temperature within adequate time. Hence the grade of heating demand can spread over certain ranges, which however can be neglected as those elements are indicated as heat sinks. The rest of the components produce enough waste heat to consider them as heat sources in steady-state cases. Thereby the importance of synergy effects emerges. The cooling system should provide capabilities to shift waste heat of appropriate components to those with heating demand instead of transferring it to the environment.

3.1.2 Propulsion Mode

Due to two propulsion modes the vehicle is either propelled by the internal combustion engine, the electric engine or by a combination of both. In case of a combined propulsion the exact distribution of the momentum is negligible. This simplification allows a categorisation as a heat source for active components. The uninvolved (passive) engine appears neutral to the cooling system. That brings up the topic of the internal combustion engines' warm up. As long as the internal combustion engine and the catalytic converter have not reached operating temperature the emission of exhaust gases runs risk to infringe regulations.

3.1.3 Driving Operation

Within the driving operation complex processes take place which influence each other and can hardly be understood without full access to measurement data and control strategy data for all components. Therefore the investigation has concentrated on the events that directly affect the cooling system and has left indirect connected processes aside. For example the internal combustion engine's management and the combustion processes have been completely neglected in order to only consider that dissipation heat is transferred to the cooling system. Thereby a simplified differentiation has been made between a warm up case when the vehicle is put to operation and a steady-state case when the vehicle has been in operation for a while and all the components have reached their operating temperatures. The sharing of those two cases during the lifecycle of a hybrid vehicle can be estimated properly today, which has direct effect on the evaluation of the cooling system design regarding the utilisation of synergy effects described in section 3.2.

3.1.3.1 Warm Up Case

During a warm up the components heat up from ambient temperature to their operating temperature. As mentioned in section 3.1.2, section 1.3.2 and section 1.3.3 warm up phase should be as short as possible to reduce exhaust gas emissions, friction losses and additional energy consumption. Synergy effects should be utilised, if possible.

3.1.3.2 Steady State Case

The components have already reached their operating temperature. If the dimensioning of the heat exchangers, the interconnections of the cooling system and the coolant and refrigerant volume flows are correct heat input and output should be balanced. The component temperatures would range in required levels.

3.1.4 Special Events

Three additional scenarios are considered which complete the reflection of the hybrid vehicle operation.

- In case of single propulsion mode the preparation of the other propulsion mode is taken in account. If the vehicle is used in combustion mode, the preparation of electric mode means the tempering of the battery to ensure maximum power output (warm up) and avoid cell damage (cool down). If the vehicle is used in electric mode, the preparation is done by acceleration of the combustion engine's warm up respectively the preheating of the catalyst taking into account that combustion efficiency and compliance of exhaust gas emission limitations require components at operating temperature.
- The second scenario is represented by the use of the refrigerant circuit in heat pump mode in winter and warm up cases. The advantage of a heat transfer from the ambiance into the cooling system shall be taken for an additional heat source.
- The third case is the preconditioning of the vehicle when it is parked and exposed to ambient temperatures. Similar to the preparation of the other propulsion mode the battery, the cabin and the internal combustion engine should reach operating temperature when the vehicle is put into operation. Even the transmission can be seen as a heat sink to lower friction losses, but the energetic effort must not exceed efficiency gains in driving operation. Thereby the possibility of external energy input shall be neglected in order to avoid dependency to external sources.

3.1.5 Overview of Usecases

The combination of these discussed cases provides 21 usecases that cover all of the occurring operating conditions for the cooling system.

Usecase	Operation	Propulsion	Ambiance	Special
1.	Warm Up	Combustion	Winter	
2.	Warm Up	Combustion	Winter	Heat Pump
3.	Steady state	Combustion	Winter	
4.	Steady state	Combustion	Winter	Preparation
5.	Warm Up	Combustion	Summer	
6.	Steady state	Combustion	Summer	
7.	Steady state	Combustion	Summer	Preparation
8.	Warm Up	Electric	Winter	
9.	Warm Up	Electric	Winter	Heat Pump
10.	Steady state	Electric	Winter	
11.	Steady state	Electric	Winter	Preparation
12.	Warm Up	Electric	Summer	
13.	Steady state	Electric	Summer	
14.	Steady state	Electric	Summer	Preparation
15.	Warm Up	Combination	Winter	
16.	Warm Up	Combination	Winter	Heat Pump
17.	Steady state	Combination	Winter	
18.	Warm Up	Combination	Summer	
19.	Steady state	Combination	Summer	
20.	Precond.	Combination	Winter	
21.	Precond.	Combination	Summer	

Table 3.1: List of usecases

These usecases are the basis for an examination scheme to develop and evaluate cooling system designs as described in section 3.4.

3.1.6 Component Behaviour

Depending on the usecases the thermal component behaviour is categorised. For the definitions of heat sources and heat sinks different processes have to be considered depending on the usecase preconditions:

- Heat sink:
  - Steady state: The heat sink demands heating to maintain operating temperature due to thermal losses (cabin).
  - Warm up / Steady state, preperation, winter: The heat sink demands heating to raise its thermal mass from ambient temperature to operating temperature (internal combustion engine, transmission, cabin, battery).
- Heat source:
  - Steady state: The heat source demands cooling to remove waste heat and/or disipation power to maintain operating temperature (internal combustion engine, transmission, charge air, electric motor, power electronics, cabin, battery).
  - Warm up / Steady state, preperation, summer: Either the heat source demands cooling to lower its thermal mass from actual temperature to operating temperature (cabin, battery), or the heat source delivers waste heat because the thermal mass has not to be warmed up (exhaust gases, charge air, electric motor, power electronics).
- Neutral element: does not demand heating or cooling.

The exhaust gases do not demand cooling to maintain operating temperature, they can be used as an additional heat source, if heating demand exceeds actual heat supply.

Usecase	ICE	TRANS	Ex.G.	C.Air	E.Mot.	PE	Cab.	Batt.
1.	SIN	SIN	SOU	SOU	NEU	NEU	SIN	NEU
2.	SIN	SIN	SOU	SOU	NEU	NEU	SIN	NEU
3.	SOU	SOU	SOU	SOU	NEU	NEU	SIN	NEU
4.	SOU	SOU	SOU	SOU	NEU	NEU	SIN	SIN
5.	SIN	SIN	SOU	SOU	NEU	NEU	SOU	NEU
6.	SOU	SOU	SOU	SOU	NEU	NEU	SOU	NEU
7.	SOU	SOU	SOU	SOU	NEU	NEU	SOU	SOU
8.	NEU	SIN	NEU	NEU	SOU	SOU	SIN	SIN
9.	NEU	SIN	NEU	NEU	SOU	SOU	SIN	SIN
10.	NEU	SOU	NEU	NEU	SOU	SOU	SIN	SOU
11.	SIN	SOU	NEU	NEU	SOU	SOU	SIN	SOU
12.	NEU	SIN	NEU	NEU	SOU	SOU	SOU	SOU
13.	NEU	SOU	NEU	NEU	SOU	SOU	SOU	SOU
14.	SIN	SOU	NEU	NEU	SOU	SOU	SOU	SOU
15.	SIN	SIN	SOU	SOU	SOU	SOU	SIN	SIN
16.	SIN	SIN	SOU	SOU	SOU	SOU	SIN	SIN
17.	SOU	SOU	SOU	SOU	SOU	SOU	SIN	SOU
18.	SIN	SIN	SOU	SOU	SOU	SOU	SOU	SOU
19.	SOU	SOU	SOU	SOU	SOU	SOU	SOU	SOU
20.	SIN	SIN	NEU	NEU	NEU	NEU	SIN	SIN
21.	SIN	SIN	NEU	NEU	NEU	NEU	SOU	SOU

Table 3.2**:** Component Behaviour

3.2 Synergy Effects

As discussed in section 3.1.6 the concurrent appearance of a heat source and a heat sink would allow utilisation of synergy effects. That is the transfer of heat from a source to a sink via the cooling system. As shown in table 3.2 the utilisation of synergy effects only arises in winter and warm up cases. Therefore the positive effects of the synergy effect usage has to be opposed to the additional effort of the hardware requirement, the complexity in control strategy and other negative effects of the cooling system design. But before the synergy effects can be analysed some mandatory principles have to be considered:

I. The design of the cooling system needs to facilitate the transfer of heat from a source to a sink. That is why the knowledge of the component behaviour directly determines the interconnection design of the cooling system.

II. The amount of heat transferred must fit the requirements given by thermal mass of the involved components. The thermal mass of the internal combustion engine exceeds the others by far. Therefore a warm up by other components' power dissipation is practically impossible.

III. A limiting factor is the temperature level at which the heat is brought into the cooling system. Thermodynamically heat can easily be transferred from a high temperature level to lower levels. The shift from lower levels to a higher level can only be achieved indirectly by the use of a refrigerant circuit.

With these specifications the utilisation of synergy effects regarding the behaviour in the usecases is evaluated for every component.

3.2.1 Transmission

The transmission can mainly be seen as a heat source due to the high temperature level. Especially in winter cases with electric propulsion power dissipation could be used to heat the battery and the cabin. To accelerate the warm up of the internal combustion engine waste heat could be used in preparation case when propulsion is changed from pure electric to combination or combustion mode. In case of warm up in pure electric mode power dissipation of the electric engine and the power electronics could be used to accelerate warm up of the transmission oil. Because of the difference in the operating temperature levels only a minor positive effect can be expected, extra connections in the cooling system design for this special purpose can not be justified.

3.2.2 Internal Combustion Engine

As it is state of the art dissipation power must be used to heat the cabin and the battery. Nowadays the warm up of the internal combustion engine is a bit quicker than that of the transmission oil. Therefore a connection between the internal combustion engine and the transmission seems reasonable.

3.2.3 Charge Air and Exhaust Gases

The behaviour is directly connected the internal combustion engine and the relatively high temperature level would allow a heat transfer to the cabin and the battery in winter cases and to the transmission oil in warm up cases. The heat of the exhaust gases could even accelerate the internal combustion engine's warm up.

3.2.4 Electric Engine and Power Electronics

In case of pure electric propulsion and winter cases power dissipation should be used to support cabin and battery heating or to accelerate the warm up of the transmission oil.

3.2.5 Cabin and Battery

The cabin and battery only operate as heat sources in summer cases. Combined with the low temperature level these components can not reasonably be used as heat sources.

3.2.6 List of Synergy Effects

Number	Heat Source	Heat Sink
1.	Internal Combustion Engine	Cabin
2.	Internal Combustion Engine	Battery
3.	Internal Combustion Engine	Transmission
4.	Transmission	Battery
5.	Transmission	Cabin
6.	Transmission	Internal Combustion Engine
7.	Exhaust Gases	Cabin
8.	Exhaust Gases	Battery
9.	Exhaust Gases	Transmission
10.	Exhaust Gases	Internal Combustion Engine
11.	Charge Air	Cabin
12.	Charge Air	Battery
13.	Charge Air	Transmission
14.	Electric Engine	Cabin
15.	Electric Engine	Battery
16.	Electric Engine	Transmission
17.	Power Electronics	Cabin
18.	Power Electronics	Battery
19.	Power Electronics	Transmission

Table 3.3: List of Synergy Effects

3.3 Cooling System Requirements

Besides the capability to transfer the entire amount of waste heat to the ambiance in all driving operations four fundamental objectives have been set to achieve progress in the problem area described in section 1.4.

I. Construction space: One of the main problems in the hybrid vehicle design is the shortage in construction space. The technical approach to a new cooling system design is to reduce the number of heat exchangers to the ambiance to an absolute minimum.

II. Synergy effects: Due to a lack of heat sources in electrified personal transportation the utilisation of synergy effects shall be enabled by the interconnection design of the cooling system to minimise extra energy use.

III. Limitation of the refrigerant circuit performance: The performance of the refrigerant circuit must be kept as low as possible due to significant energy consumption for heat removal. The dimensioning of the heat exchangers, which directly correlates with the cycle performance, must not exceed the limitations given by the construction space.

IV. "Heat Distribution Unit": To have an additional progressive simplification in the cooling system's hardware design another target is to have a black box to which all the components are connected. Inside this black box all the interconnections, the coolant distribution and the cooling control should be executed.

These constraints lead to a concept development procedure, which bases on the four objectives above and evolves in the examination scheme given by the usecases.

3.4 Concept Development Procedure

The concept development procedure has been carried out step by step and executed in loops:

I. A general hybrid vehicle with all the discussed components has been assumed.

II. Disregarding the exact specifications of the hardware components different cooling system designs have been sketched pursuing two goals:
   - Meet the cooling system requirements as described in section 3.3.
   - Compliance of the operating temperature level restrictions as shown in figure 1.5.

III. Disregarding the necessary valves and coolant pumps in the first place the theoretical heat flows within the cooling circuits have been illustrated for all usecases to determine the necessary interconnections between the applied components and to reveal insufficiencies in the concept.

IV. The result has been evaluated by concerns of:
   - resulting intersections within the piping system

- number of interior heat exchangers (changing heat between circuits not components or ambiance)
- estimated number of valves
- estimated number of pumps
- number of utilised synergy effects
- estimated advantage by the utilisation of synergy effects: acceleration of component warmup
- amount of estimated energy consumption for coolant supply
- estimated cooling control complexity
- thermodynamic feasibility

V. A dissatisfying result has lead to a new design concept which evolved out of the insufficiency of the previous design. Additionally important influence factors that have shown up in the development process have been integrated in the next loop.

Chapter 4

Simulation

To examine the assumptions made in the concept development process a steady-state simulation of the last two concepts has been done with the simulation software KULI® showing that othe last concept meets the requirements for a maximum speed drive case.

4.1 Software

KULI® is a 1 - D numerical simulation software developed by Engineering Center Steyr (Magna Powertrain). Supporting steady-state and transient simulations this software provides an implemented air path, heat transfer and coolant behaviour within the cooling system. The actual vehicle geometries and experienced respectively measurement data set up the simulation boundary conditions. The simulation is run by the driving operation (steady-state) - or the driving cycle (transient) data and provides information of component and fluid temperatures, pressure losses, volume flows and amounts of transferred heat. The software is used by automotive industry to design and evaluate cooling systems for all kinds of vehicles according to the work flow shown in figure 4.1.

4.1.1 Cooling Air Flow

Based on the streamline theory KULI operates with the non-dimensional pressure coefficient cp, which is directly related to the velocity of the air flow. Us-

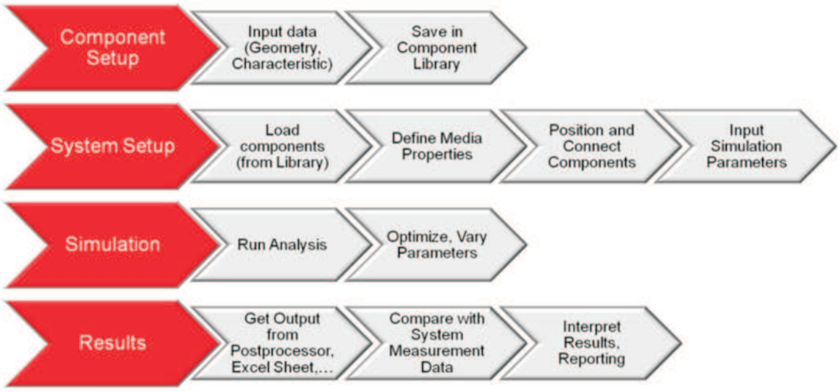

Figure 4.1: KULI® workflow [Engineering Center Steyr, 2012]

ing the Bernoulli equation shown in equation 4.1 for incompressible fluids the pressure losses occurring within the air flow through the engine compartment are calculated [Engineering Center Steyr, 2010, p.1].

$$p_1 + \rho \cdot g \cdot z_1 + \frac{\rho}{2} \cdot {v_1}^2 = p_2 + \rho \cdot g \cdot z_2 + \frac{\rho}{2} \cdot {v_2}^2 \tag{4.1}$$

This can happen in different ways depending on the origin of the cp-values.

$$\Delta p = cp \cdot \frac{\rho}{2} \cdot (v_\infty - v_{inlet})^2 \tag{4.2}$$

$$\Delta p = cp \cdot \frac{\rho}{2} \cdot {v_\infty}^2 \tag{4.3}$$

$$\Delta p = \frac{\rho}{2} \cdot (cp \cdot v_\infty^2 - v_{inlet}^2) \tag{4.4}$$

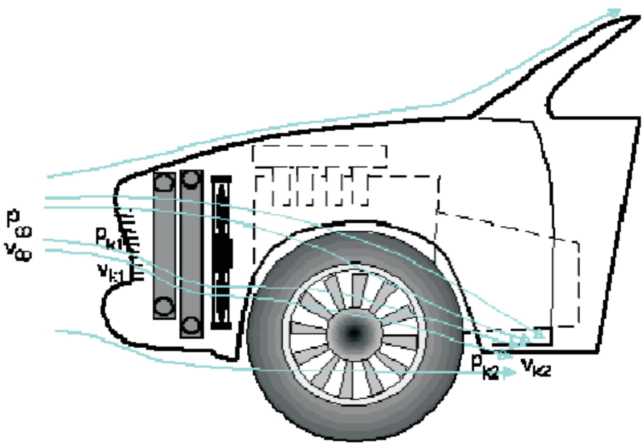

Figure 4.2: Cooling Air Flow [Engineering Center Steyr, 2012]

4.1.2 Air Resistances

The modeling of the air flow through complex geometries can be done by recalculation of measurement data. The touched area is neglected and a built in resistance is modeled in a plane normal to the flow direction. The characteristic length for the volumetric flow is set to 1 m, related to 1 m^2 cross section area [Engineering Center Steyr, 2010, p.3].

$$\xi = \frac{2 \cdot \Delta p_{stat}}{\rho \cdot v} \tag{4.5}$$

$$\text{Re} = \frac{\nu \cdot L}{v} \tag{4.6}$$

$$v = \frac{\dot{V}}{1} \tag{4.7}$$

If the touched area (breadth b, height h) has distinct influence to the pressure drop, the area is taken in account for the calculation of the flow velocity [Engineering Center Steyr, 2010, p.4].

$$v = \frac{\dot{V}}{b \cdot h} \tag{4.8}$$

4.1.3 Heat Transfer

" The heat transfer performance of a radiator is given from the streams of thermal capacities of the medium going through, the magnitude of flows and the temperature differences appearing. If no heat transfer to a third medium is occurring, then the heat flow emitted by the warmer medium (water) can only be as high as it can be absorbed by the colder medium (air)" [Engineering Center Steyr, 2010, p.11]:

$$\dot{Q} = W_I \cdot (T_{I(in)} - T_{I(out)}) \tag{4.9}$$

$$\dot{Q} = W_O \cdot (T_{O(in)} - T_{O(out)}) \tag{4.10}$$

$$W_I = \dot{m}_I \cdot c_{pI} = w_I \cdot \rho_I \cdot A_I \cdot c_{pI} \tag{4.11}$$

$$W_O = \dot{m}_O \cdot c_{pO} = w_O \cdot \rho_O \cdot A_O \cdot c_{pO} \tag{4.12}$$

" Viewing the cooling package (whole system), which is composed of several heat exchangers for water, air, oil and other media, the components are divided up into single parts corresponding their geometrical overlapping. For each of this parts a heat balance attending cooling air (outer circuit) and coolants (inner circuit) is prepared. The complexity of cross flow heat exchangers requires describing the heat transfer of each element with the operating characteristic Φ" [Engineering Center Steyr, 2010, p.12].

$$\dot{Q} = W_k \cdot (T_{I(in)} - T_{O(in)}) \cdot \Phi \tag{4.13}$$

4.1.4 Operating Characteristic according to Shedwill

> “ The operating characteristic for cross flow heat exchangers with N number of rows according to Schedwill is given as:” [Engineering Center Steyr, 2010, p.16, quoted in accordance with Schedwill H., 1968, p.79f.]

$$\Phi = \frac{W_I}{W_O}\left\{1 - \frac{1}{N}\left[1 + \sum_{p=1}^{N-1}\sum_{m=0}^{p}\begin{pmatrix} p \\ m \end{pmatrix}\left(1 - e^{-\frac{1}{N}\frac{kA}{W_O}}\right)^m \right.\right.$$
$$\left.\left. e^{-(p-m)\frac{1}{N}\frac{kA}{W_O}}\sum_{r=0}^{m}\frac{\left(\varepsilon y_0\right)^r}{r!}\right] e^{-\varepsilon y_0}\right\} \tag{4.14}$$

for $W_1 < W_0$ and

$$\Phi = 1 - \frac{1}{N}\left[1 + \sum_{p=1}^{N-1}\sum_{m=0}^{p}\begin{pmatrix} p \\ m \end{pmatrix}\left(1 - e^{-\frac{1}{N}\frac{kA}{W_O}}\right)^m e^{-(p-m)\frac{1}{N}\frac{kA}{W_O}}\sum_{r=0}^{m}\frac{\left(\varepsilon y_0\right)^r}{r!}\right] e^{-\varepsilon y_0} \tag{4.15}$$

for $W_1 > W_1$. With

$$\varepsilon y_0 = \frac{W_O}{W_I}N\left(1 - e^{-\frac{1}{N}\frac{kA}{W_O}}\right) \tag{4.16}$$

4.1.5 Operating Characteristic from Measured Maps

> “ To determine the operating characteristic the heat transition coefficient of a radiator has to be evaluated from measured thermal output maps.The measurements give the inlet- and outlet temperatures and the velocities. From these values the thermal output can be calculated” [Engineering Center Steyr, 2010, p.19].

For calculations that do not base on the exact boundary conditions of the measurement data it is necessary to transform the heat exchanger performance data into a non-dimensional data. This conversion is achieved by the use of the Nusselt number for both mediums and executed in three steps:

I. The Reynolds numbers for the inner and the outer mediums are calculated by:

$$\mathrm{Re}_I = \frac{w_I \cdot L_{char}}{\nu} \tag{4.17}$$

$$\mathrm{Re}_O = \frac{w_O \cdot L_{char}}{\nu} \tag{4.18}$$

with

$$w_I = \frac{\dot{m}_I}{A \cdot \rho} \tag{4.19}$$

and

$$w_O = \frac{\dot{m}_O}{A \cdot \rho} \tag{4.20}$$

.

II. As the Nusselt number is a function of the Reynolds numbers of the inner and outer mediums

$$Nu^* = f(\mathrm{Re}_I, \mathrm{Re}_O) \tag{4.21}$$

the heat transition coefficient can be calculated by

$$Nu^* = \frac{k_A \cdot L_{char}}{\lambda} \tag{4.22}$$

.

III. The operating characteristic of can be determined as all the influence factors are known now

$$\Phi = f(N, W_O, W_I, A_O, k_A) \tag{4.23}$$

and outlet temperatures can be calculated by given (measured) inlet temperatures:

$$T_{O(out)} = T_{O(in)} - (T_{O(in)} - T_{I(in)}) \cdot \Phi \cdot \frac{W_k}{W_O} \tag{4.24}$$

$$T_{I(out)} = T_{I(in)} + (T_{O(in)} - T_{I(in)}) \cdot \Phi \cdot \frac{W_k}{W_I} \tag{4.25}$$

4.2 Simulation

After several concept development procedure loops the concept “Merging Circuits” described in section 5.2.4 has been examined particularly. As shown in figure 5.7 the two inevitable cooling circuits for high temperatures (supplying internal combustion engine, transmission and exhaust gases) and for low temperatures (battery and cabin) have been merged to generate the suitable temperature level for charge Air, electric motor and power electronics. Thereby all listed synergy effects can be utilized without heat exchange losses. Additionally the possibility of heat buffering expands the scope of thermal management in critical driving operations, since heat can be shifted between all components in this concept.

4.2.1 Specific Hybrid Vehicle

To investigate and evaluate the concept “Merging Circuits” a specific hybrid vehicle has been chosen. The vehicle described in section 2.1 is a mid size sedan with a turbocharged diesel engine, a wide range battery and a relatively powerful electric engine. Because of the high performance data respectively high power dissipation this vehicle has been chosen to experience the heat flows explicitly. Since simulation modeling data and measurement data are available as well as parts of other models can be used to set up a suitable simulation model.

4.2.2 Structure

The high temperature circuit supplying internal combustion engine and transmission has been implemented with a cross counterflow radiator divided in two sections. After the first section the coolant volume flow has been split. One part directly supplying the internal combustion engine and the transmission, the other part passing through the second section of the radiator to be part of the supply of the charge air cooling, the power electronics and the electric engine cooling representing the mid temperature level. On the other hand the battery supply constituted by a coolant circuit discharging heat by a chiller. A variable part of this coolant flow is added to the supply for the mid temperature components depending on the driving operation. The structure can be seen in figure 5.6.

4.2.3 Model

The model is the direct implementation of the sketched design developed according to the acquired procedure described in section 3.4. Based on company's simulation data a model has been set up using researched model fragments to emulate a hybrid vehicle model. The model itself basically operates with characteristics curves based on measurement data to put out heat quantities referring to driving conditions like rotational speed, loads and component temperature. Since the regulation of the thermal management has not been part of this investigation only a steady-state driving cases have been researched.

4.2.4 Subsystems

The simulation model consists of different subsystems that build the mathematical modules for the physical representation of the hybrid vehicle. One subsystem for example calculates the required propulsion power for the actual driving situation in the following way:

$$P_{Wheel} = (F_a + F_{asc} + F_R) \cdot v_{Veh} \tag{4.26}$$

with the required force for acceleration:

$$F_a = m_{Veh} \cdot a_{Veh} \tag{4.27}$$

and the required force of ascent for given q [%] and α :

$$\frac{q}{100} = \tan(\alpha) \tag{4.28}$$

$$F_{asc} = m_{Veh} \cdot \sin(\alpha) \tag{4.29}$$

and the required force to get over driving resistances:

$$F_R = f_0 + f_1 \cdot v_{Veh} + f_2 \cdot {v_{Veh}}^2 \tag{4.30}$$

$$F_R = m_{Veh} \cdot g \cdot C_{rr} + f_1 \cdot v_{Veh} + c_d \cdot A_{Veh} \cdot \frac{\rho_{Air}}{2} \cdot {v_{Veh}}^2 \tag{4.31}$$

4.2.5 Simulated Case

The steady-state key hardship case for the cooling system is maximum speed drive. It displays maximum power output of the internal combustion engine in combination with electric motor propulsion. The ambient temperature is set to 45 °C and induces unpropitious conditions for heat removal. In case of the investigated vehicle the maximum speed ranges to 262 km/h with the transmission operating at seventh gear. The required wheel driving power is 170 kW, including the auxiliary device power it is 197 kW, which is provided by the internal combustion engine (80 %) and the electric engine (20%).

Chapter 5

Results

DURING the investigation several cooling system designs have passed the concept development process. In the following section the advantages and disadvantages of these designs are discussed and general findings about cooling system design principles are presented. The results of the simulation have shown that there are capabilities in cooling system designs to reduce construction space allocation and to utilise synergy effects in certain operating conditions.

5.1 Component Pooling

The precept of two heat exchangers to the ambiance combined with the fact that the operating temperatures of the components strongly differ necessitate the pooling of suitable components to independent cooling circuits. Thermodynamics leaves little scope in pooling as shown in figure 5.1. Obviously the “hot” components exhaust gas, internal combustion engine and transmission have to be pooled to a circuit that is supplied by a radiator, because operating temperatures allow heat removal by coolant. The “cold” components cabin and battery have to be supplied by a refrigerant cycle, because ambient temperatures often exceed their operating temperatures. Left inbetween the “warm” components charge air, electric motor and power electronics have to be integrated into the cooling system anyhow. Therefore different cooling system designs have been developed based on the development procedure described in section 3.4.

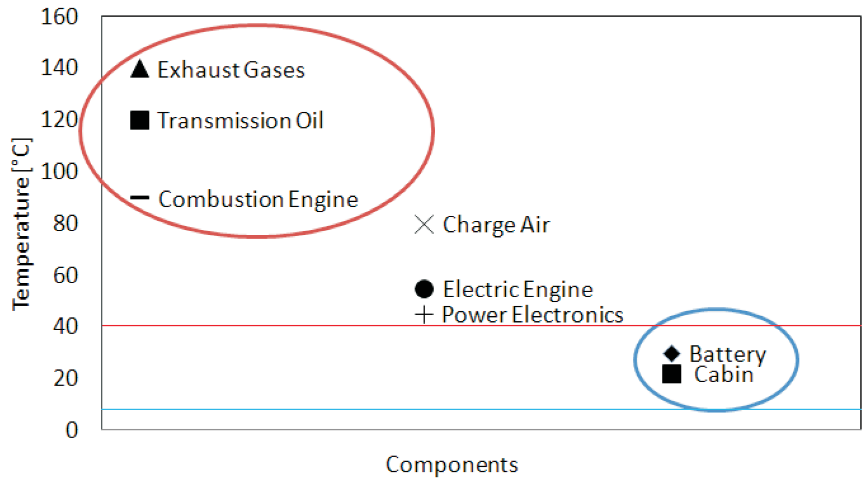

Figure 5.1: Component Pooling

Several insights about false assumptions during the development process have come at the end of the investigation. That is why unnoticed disadvantages in early design concepts have been brought into the next design step but can be named at the end of this investigation. The theoretical heat flow analysis for the introduced usecases can be seen in the appendices for the following cooling system concepts.

5.2 Cooling System Design Concepts

BAT	Battery	ICE	Internal combustion engine
COND	Condenser	INT	Intercooler
CAT	Catalyser	LTC	Low temp. cooler
EM	Electric motor	PE	Power electronics
EVAP	Evaporator	RAD	Radiator
EG	Exhaust gases	TC	Turbo charger
HX	Heat exchanger	TRANS	Transmission

Table 5.1: Component abbrevaiations

5.2.1 Concept: Valve Circuit

The first design concepts have disregarded the charge air and the exhaust gases as a component which has been changed later on. The technical approach was to utilise as many synergy effects as possible, what lead to an intricate design

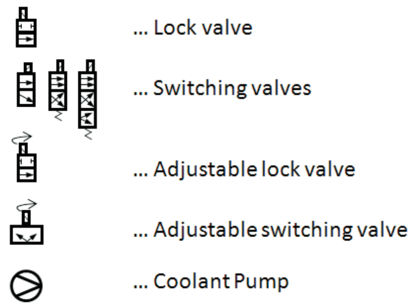

Figure 5.2: Icon description

applying many valves and an extra heat exchanger to have wide flexibility in shifting heat between the components. Thereby the "warm" components electric motor and power electronics were integrated into the "hot" circuit whereas the right inlet temperatures were achieved by the use of the heat exchanger which transferred the heat to the refrigerant cycle.

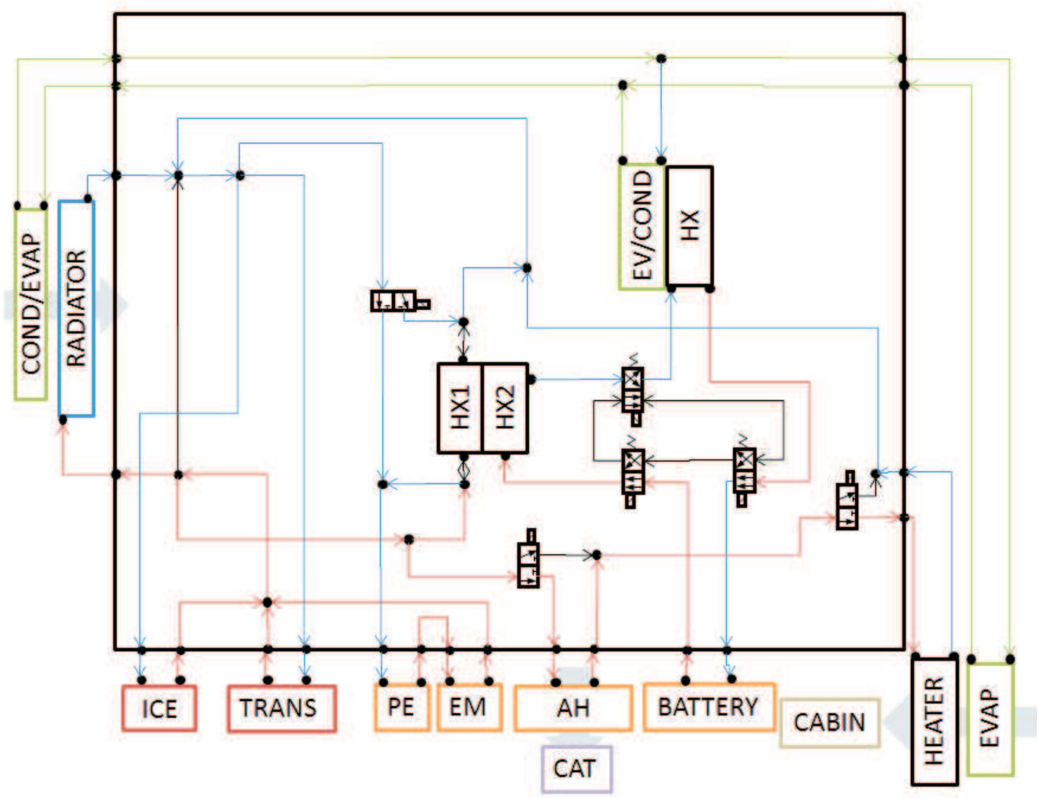

Figure 5.3: Concept: Valve Circuit

Advantages:

- Wide flexibility in heat shifts between components.
- Heat pump mode of the refrigerant cycle possible.

Disadvantages:

- The mixture of the refluxes of the internal combustion engine/transmission and the electric motor/power electronics is thermodynamically not reasonable, because the simulation of the concept "Merging Circuits" (5.2.4) has shown that this shifts heat removal from the radiator to the refrigerant cycle. This is energetically adverse and quite likely exceeds the maximum performance of the refrigerant cycle.
- Large number of valves.
- Cooling of electric engine and power electronics by the use of the refrigerant circuit lowers efficiency in heat removal.
- Disregarding of charge air and exhaust gases.

5.2.2 Concept: Two Radiators

The technical approach of this concept has been the application of a radiator for the "cold" components with direct integration of the "warm" components. Namely there are two options to realise heat removal for the "cold" and "warm"components.

I. The first option is to use the refrigerant condenser as heat exchanger to the ambiance as shown in figure 5.8. This allows to reduce the number of heat exchanger components to two. On the other hand all the dissipation heat of the battery, electric motor and power electronics has to be removed by the use of the refrigerant cycle. This is because of two reasons:

    - The mixture of coolants with different temperature levels for supply of different operation temperatures as shown in figure 5.6 is thermodynamically not reasonable, because it either effects extra cooling demand or lowers the efficiency of heat transfer. Therefore the coolant supply for the electric components has to be decoupled from the high temperature circuits. This implies the heat removal by refrigerant cycle via the chiller for the battery as well as the electric motor and the power electronics.

- Even in pure electric mode three temperature levels have to be supplied: the battery/cabin, the electric motor/power electronics and the transmission. The transmission has to be cooled by the radiator, the battery/cabin by the refrigerant circuit so the electric motor and the power electronics can only be integrated in the battery circuit.

II. The second option is a low temperature radiator used for heat transfer to the environment as shown in figure 5.4. That induces the application of two chillers in combination with a refrigerant circuit. One chiller (evaporator) to remove heat from the battery and one chiller (condenser) to transfer the heat to the coolant for heat removal by the radiator to the environment. The benefit lies in the option to remove dissipation heat of the electric motor and the power electronics directly by the radiator without the use of the refrigerant cycle. The disadvantage is the necessity of three heat exchanger components and the fact that the cooling demand of the battery can only be satisfied by the combination of the refrigerant cycle and the coolant cycle which causes additional energy consumption.

Advantages:

- The use of a low temperature radiator allows cooling of the electric engine/power electronics without the additional power consuming refrigerant cycle.
- The refrigerant cycle can be connected to the high temperature level. Thereby the heat pump mode could replace/compensate the auxiliary heating.
- Good synergy effect utilisation possible.
- The direct connection of the high and the low level temperature circuit allows the heat shifts without heat exchanger losses.

Disadvantages:

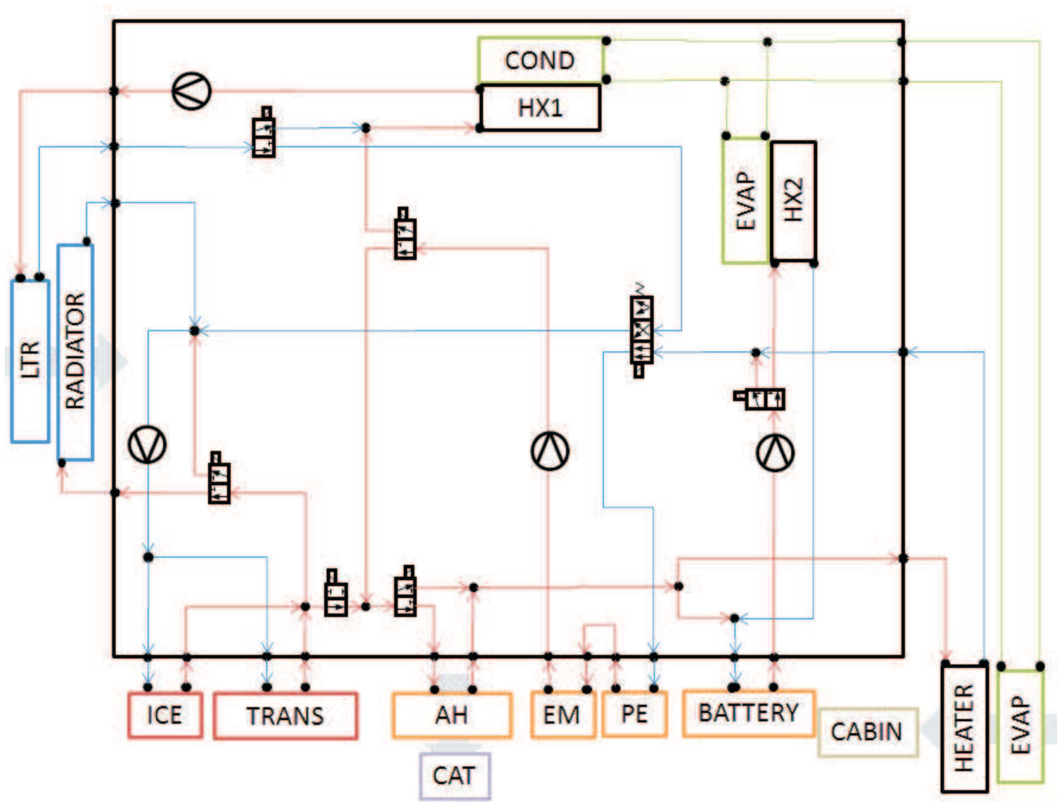

Figure 5.4: Concept: Two Radiators

- The low temperature radiator circuit has always to be run when the refrigerant cycle is active even when electric engine/power electronics/battery do not produce dissipation heat. This involves extra energy consumption.
- Great number of valves.
- Disregarding of charge air and exhaust gases.

5.2.3 Concept: Supply Ring

This concept has refined the advantages of the two previous concepts. The "hot" and the "cold" circuit have been decoupled, the heat removal is realised by independent heat exchangers, but the option of heat shift between the circuits is enabled by two valves.

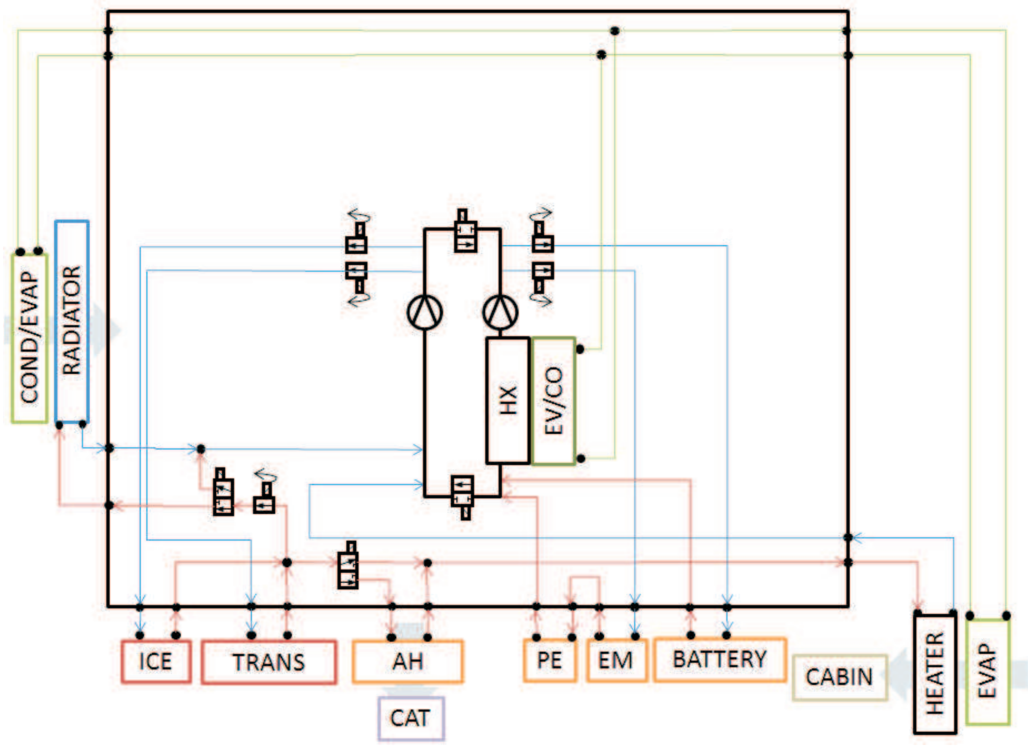

Figure 5.5: Concept: Supply Ring

Advantages:

- Quite simple design with few valves.
- Utilisation of synergy effects is possible.

Disadvantages:

- Dissipation power of electric motor/power electrics has to be removed by use of refrigerant cycle.
- Disregarding of charge air and exhaust gases.

5.2.4 Concept: Merging Circuits

The introduction of the charge air cooling has brought up a new temperature level to be supplied, which has been considered by the application of a cross counterflow radiator. This radiator has been sectioned to supply the internal combustion engine/transmission and to supply a third temperature level for the "warm" components. To compensate the temperature level difference between the charge air cooling and the electric motor/power electronics a mixture of coolant supplied by the radiator and supplied by the chiller should have resulted in suitable inlet temperatures. The simulation of this design has shown that a mixture of coolant from the "hot" and the "cold" circuit leads to a shift of heat removal from the radiator to the chiller. This effect has completely invalidated the concept, because the refrigerant cycle performance has had to exceed justifiable limits as well as the energy consumption for heat removal has been unacceptable.

Advantages:

- Provision of a third coolant temperature level by the application of a sectioned cross counterflow radiator.
- Wide adjustability for coolant temperature in "warm" temperature level.
- Utilisation of synergy effects by direct cooling system connections.
- Electric engine and power electronics to be cooled without the use of refrigerant circuit.

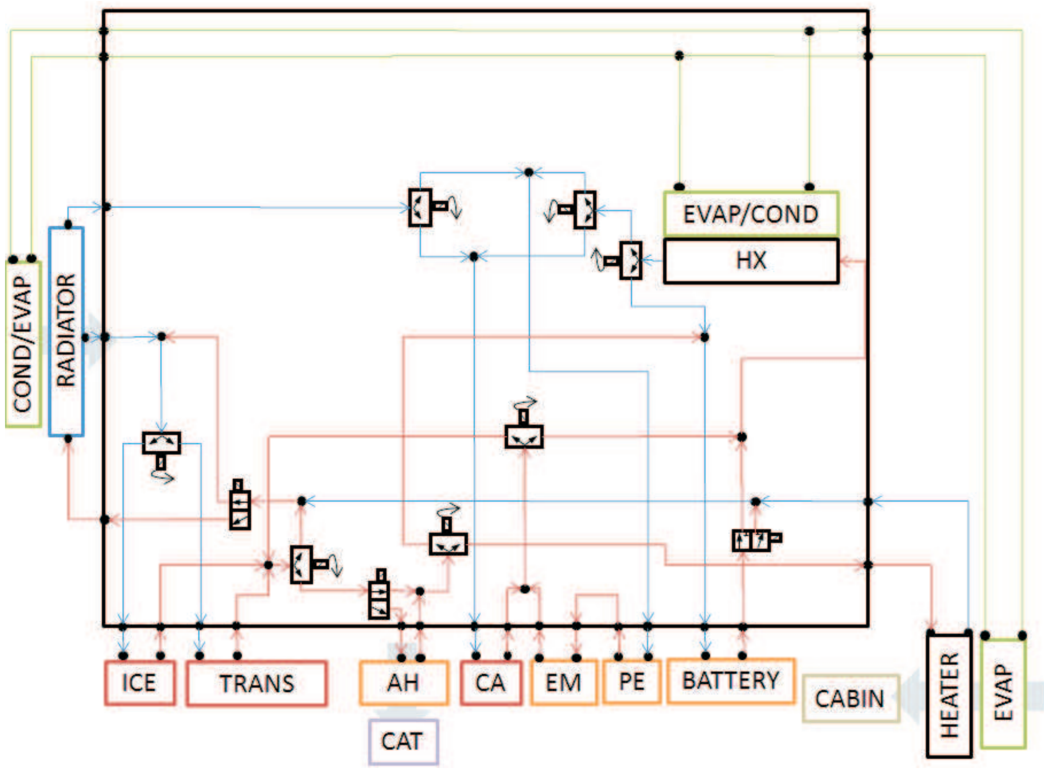

Figure 5.6: Concept: Merging Circuits

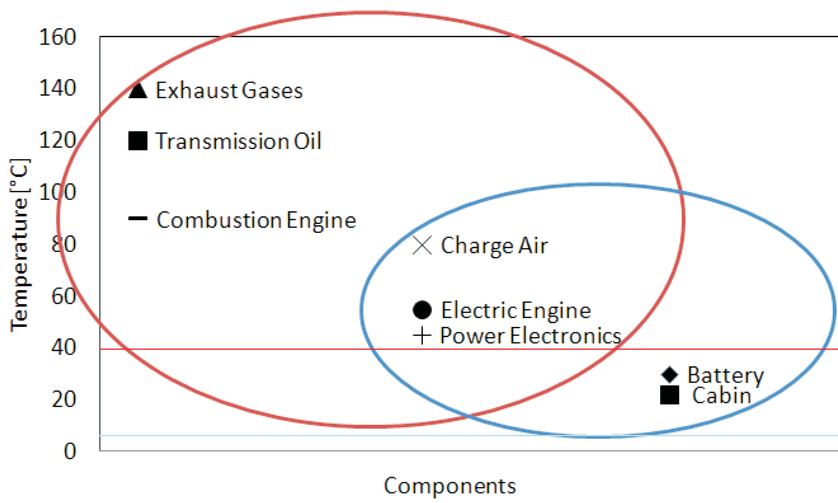

Figure 5.7: Merging of the different temperature levels for concept "Merging Circuits"

Disadvantages:

- Mixing of coolants thermodynamical completely unreasonable.
- Disregarding of exhaust gases.

5.2.5 Concept: Parallel Connection

The last concept has been a combination of the advantages of the concepts “Supply Ring” and “Merging Circuits”. The integration of the charge air has been realised by the second section of the cross counterflow radiator. The exhaust gas cooling is parallel implemented to the “hot” circuit. The temperature differences between the internal combustion engine, the transmission and exhaust gas has been adjusted by coolant volume flow. The parallel connection between the “hot” and the “cold” circuit allows the utilisation of synergy effects. The enhanced energy consumption for cooling demands of the electric motor and the power electronics has been a concession to the precept of two heat exchangers to the ambiance. Nevertheless the lower operating temperature of the electric motor and the power electronics would have positive influence to the durability of these components referring to figure 1.4.

Advantages:

- Utilisation of synergy effects by parallel cooling system connections.
- No mixture of coolant with different temperature levels is necessary.
- Durability of electric motor and power electronics improved.

Disadvantages:

- Dissipation power of electric engine/power electrics has to be removed by use of refrigerant cycle.

5.3 Design Principles

During the concept development process some principles have arisen:

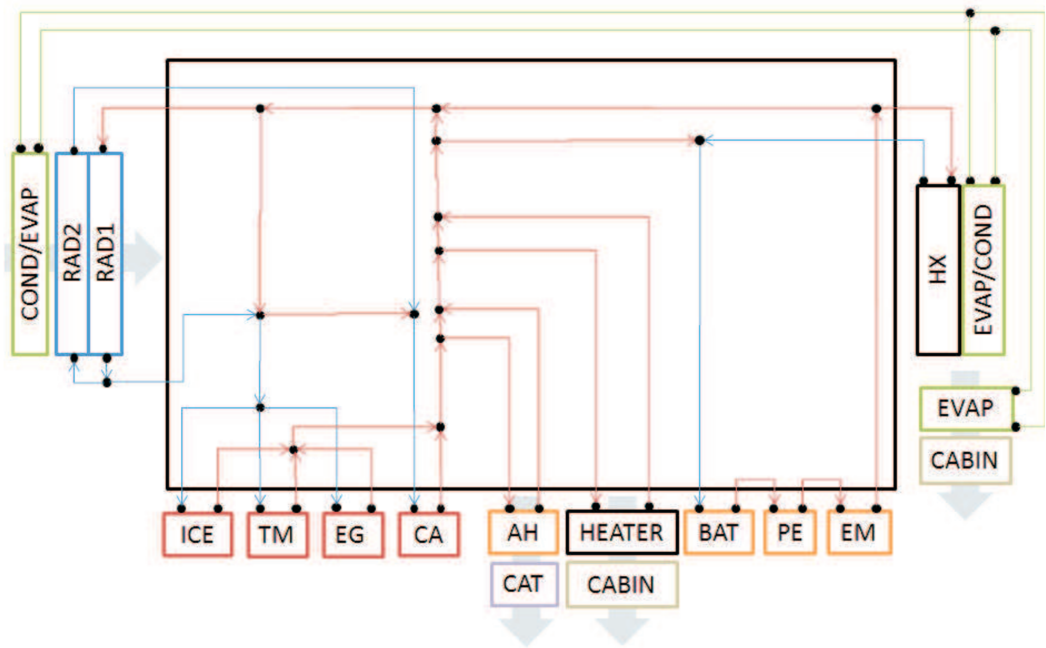

Figure 5.8: Concept: Parallel Connection

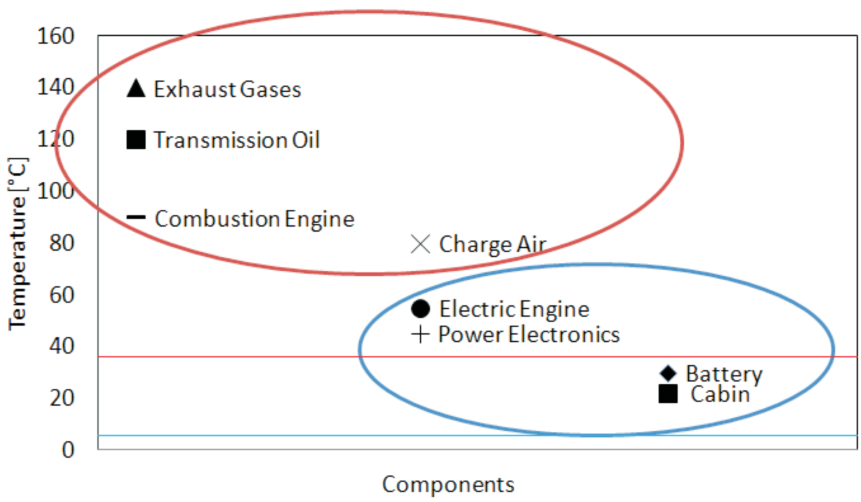

Figure 5.9: Integration of the components for concept "Parallel Connection"

I. The auxiliary heating has to be located between the internal combustion engine and the cabin heating, since the internal combustion engine represents the most powerful heat source, which needs to be used for cabin tempering for comfort reason. If the internal combustion engine is not able (off or warm up) to supply heat the auxiliary heating steps in. Additionally it can accelerate the warm up of the combustion engine if needed.

II. The internal combustion engine, the transmission and the exhaust gas cooling can be supplied with the same coolant temperature level. The different operation temperatures can be adjusted by the volume flow.

III. The charge air needs a distinct coolant temperature to guarantee high efficiency in combustion.

IV. The radiator needs a bypass to enable synergy effect utilisation within the highest temperature level components and to the other temperature level components. Moreover differences in warm up speeds can be compensated or optimised, for example the heat shift from the charge air to the internal combustion engine/transmission while warm up.

V. The auxiliary heating and the cabin heat exchanger have to be linked parallel not serially to the cooling circuit. This measure minimises pressure losses when cabin heating is provided without the need of auxiliary heating. More important the auxiliary heating can be used for warm up support even when cabin does not demand heating.

VI. The characteristic a radiator enables two options of heat removal improvement. To transfer more heat either the temperature difference between coolant and airflow or the coolant volume flow has to be increased. The limitation, besides the heat resistance of the material, is the mininmal stream of thermal capacity, as shown in equation 4.13, which cannot absorb more heat even if the other stream of thermal capacity is increased by further massflow (saturation). Combined with the thermodynamic disadvantage of coolant mixing (of different temperature levels) the temperature level of the coolant should be kept as high as possible to optimise the radiator's coefficient of performance according to equation 2.3. Hence the coolant volume can be kept low which directly corresponds to the coolant pumps' energy consumption.

VII. The control of the refrigerant circuit carried out with one condenser and two evaporators is still hard to handle, especially when a heat pump mode is planned. Therefore the components involved in the refrigerant circuit should be kept as low as possible. Additionally a heat pump mode could be executed to provide additional heat from the ambiance. This could be useful in further automotive electrification since the performance can be estimated better than of the HV-PTC.

VIII. The auxiliary heat can be provided in two different ways. Either with an electric HV-PTC, which cuts down driving range, or with a fuel burner, which is reluctantly applied for sales strategy reason, but includes the possibility of preheating the catalyser. This could improve the exhaust gas emission behaviour in warm up cases.

IX. The decision to apply two heat exchangers to the ambiance leaves two options for the design of the low temperature coolant circuit as described in section 5.2.2.

5.4 Simulation Results

By the use of the concept development procedure different cooling system architectures have been created. The evaluation of those concepts in section 5.2 pointed out that the two concepts “Merging Circuits” and “Parallel Connection” theorethically meet the requirements discussed in section 3.3. To confirm the assumptions made in the usecase heat flow sketches shown in the appendencies a simulation with KULI has been done. The simulation of transient cases requires a sophisticated control strategy for the cooling system which has to be brought into accord with the logics of the propuslion system. Also optimisation potentials concerning energy consumption and component interaction logics would have to be implemented to acchieve efficient operation.

Therefore a steady-state simulation for usecase number 19 (Steady state, combined propulsion, summer), which has been configured for maximum speed drive at 45 °C with active air conditioning. This represents the maximum workload for the cooling system and covers most of the other workloads occuring in the rest of the usecases. The operation with usual coolant volume flows has had to show if operating temperatures of all involved components range in correct levels.

The utilisation of synergy effects ccan not be shown with steady-state simulation, but it is suitable for evaluations of the basic capabilities of the cooling system.

5.4.1 Concept: Merging Circuits

The simulation of the concept "Merging Circuits" described in section 5.2.4 has shown that the mixture of different coolant temperature levels is not reasonable. As shown in figure 5.11 the suitable component temperatures can be achieved.

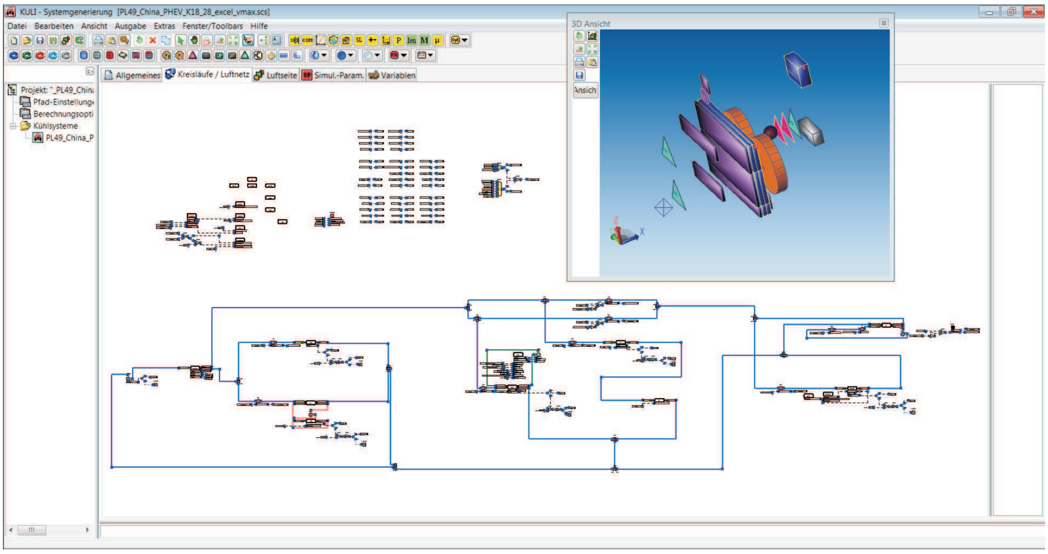

Figure 5.10: KULI-model of the concept "Merging Circuits"

However the allowed cooling performance of the refrigerant circuit has been exceeded by far as shown in figure 5.12.

The problem is the supply of the "warm" components, that need a mixture of hot and cold coolant for the right inlet temperatures. By mixing the coolants the heat removal is shifted from the radiator to the chiller respectively the refrigerant circuit as shown in figure 5.12. Even with multiple variations in coolant volume flows for every single component this effect could not have been evaded. Therefore the concept of Merging Circuits is not suitable for hybrid vehicle cooling systems.

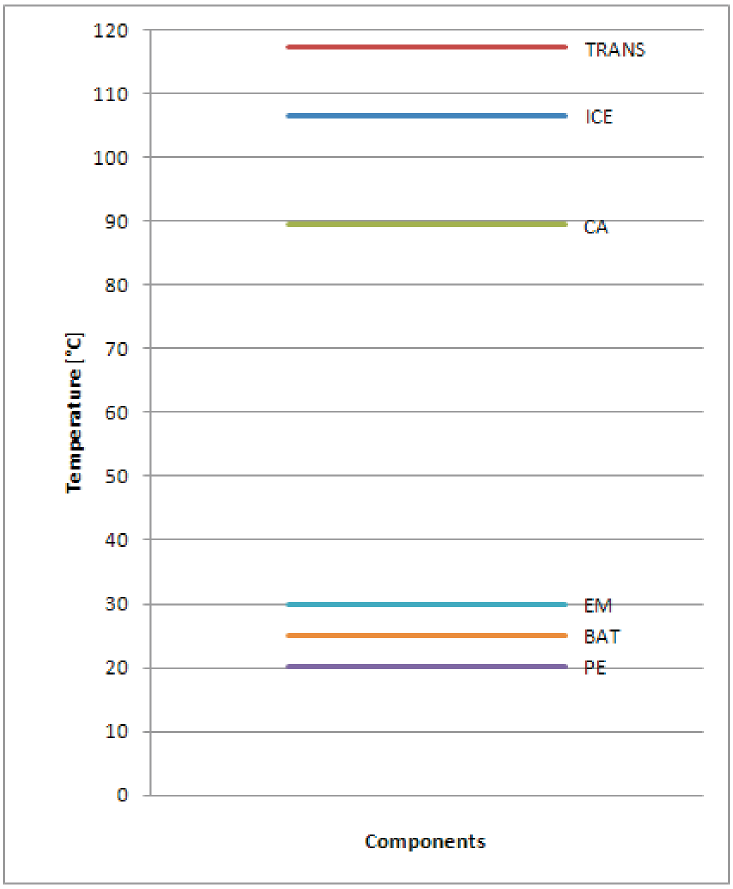

Figure 5.11: Merging Circuits: Component temperatures in maximum speed drive

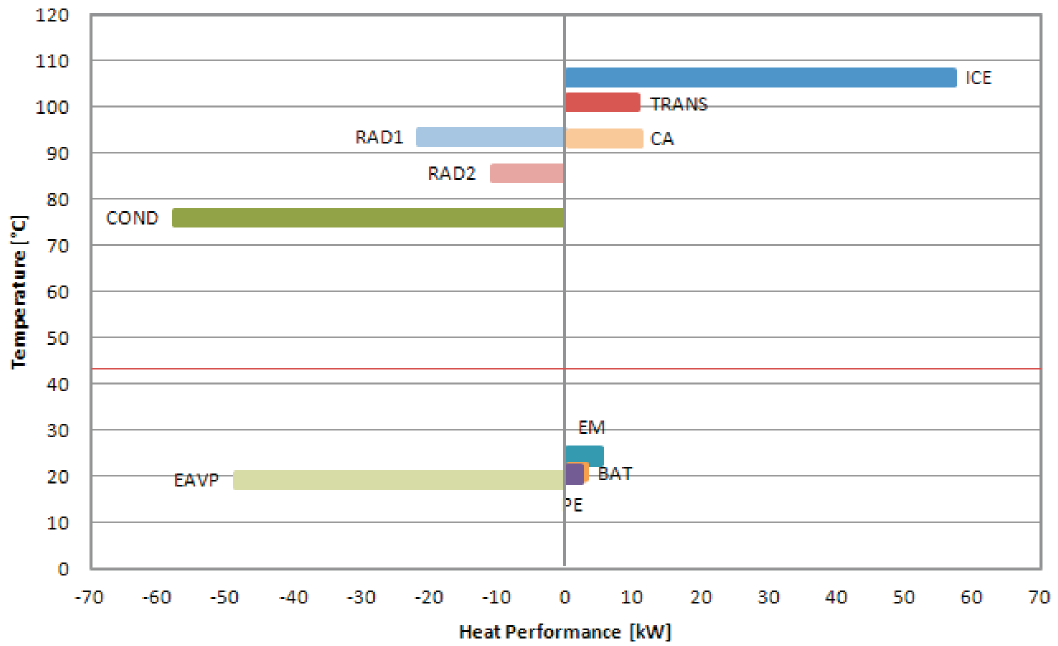

Figure 5.12: Merging Circuits: Amounts of heat transferred within the cooling systems

5.4.2 Concept: Parallel Connection

The simulation of "Parallel Connection" described in section 5.2.5 has shown that the steady-state case with maximum speed can be handled in this configuration. The component temperatures range in adequate levels as shown in figure 5.14 and the heat flows through the cooling system match the requirements as shown in figure 5.15.

The simulation has shown that in the maximum speed drive case the configuration of the cross counterflow heat exchanger is suitable to supply the internal combustion engine, the transmission and the charge air. The refrigerant circuit is able to remove the heat from the electric motor, the power electronics, the battery and the passenger compartment as shown in figure 5.15. If the cooling system design is able to utilise synergy effects in a reasonable way and meets the requirements of other driving operation cases, has to be shown in further simulation with transient cases.

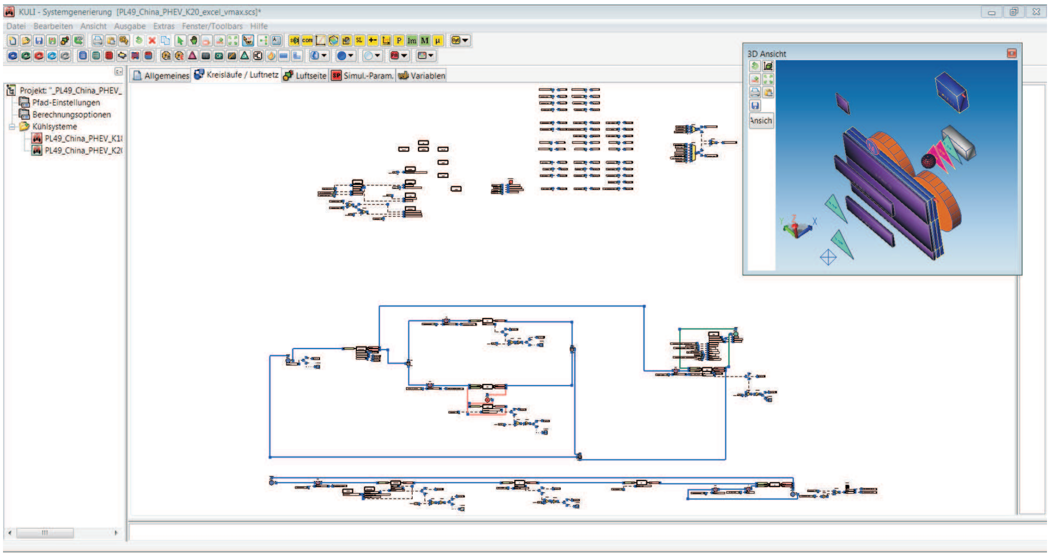

Figure 5.13: KULI-model of the concept "Parallel Connection"

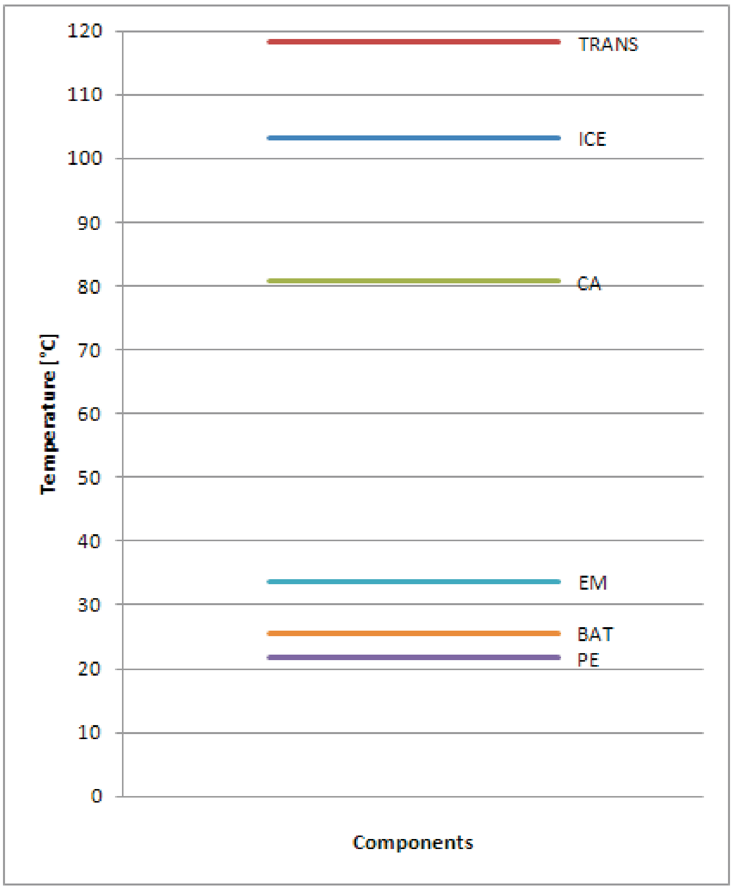

Figure 5.14: Parallel Connection: Component temperatures in maximum speed drive

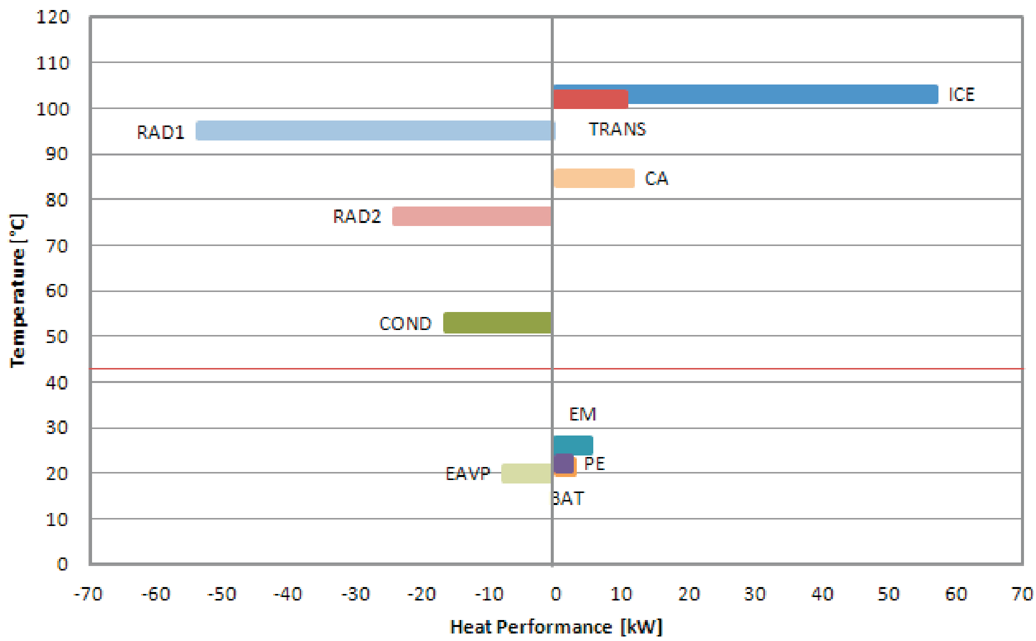

Figure 5.15: Parallel Connection: Amounts of heat transferred within the cooling system

5.5 Results of the Concept Development

After many loops of the concept development procedure the concept of "Parallel Connection" described in section 5.2.5 has been introduced which theoretically enables the utilisation of synergy effects without the disadvantage of mixing coolants of different temperature levels like the concept "Merging Circuits" described in section 5.2.4. The disadvantage of higher energy consumption for cooling of the electric components due to the radiator problems discussed in section 5.2.2 can be accepted with consideration of the two great advantages of gains in construction space and the utilisation of synergy effects. The functionality and the positive effect of synergy effect utilisation has to be shown in further simulation, which has to be executed for transient cases that show warm up processes and allows specific measurement evaluation. Furthermore the implementation with coolant pumps and valves has to be investigated regarding concerns of production costs and energy efficiency.

Chapter 6

Conclusion

In this work, the investigation has shown that cooling systems of hybrid vehicles can be further improved and optimised. The main challenges are related to different operating temperatures of components, the shortage in construction space and the increasing deficiency of heat sources for heating demands. The complex processes in driving operation were simplified by the introduction of a compound of usecases to make the components' behavior assessable and interdependencies revealable. The utilisation of synergy effects has been derived to explore capabilities of efficiency enhancement. The possibility of heat exchanger reduction and a concomitant merging of components to an integrated cooling system design has pointed out benefits in construction space allocation, exploitation and distribution of heat in critical driving situations. These measures are expected to involve increased expenditure in cooling system control and hardware implementation.

6.1 Perspective

The developed list of usecases represents rough simplifications of the hybrid vehicles' operational life cycle. The visualisation of the sketched heat flows for those usecases can be improved by the use of Q-T-diagrams (figures 5.12 and 5.15) displaying the occurring amounts of heat related to the according temperature levels. Q-T-diagrams introduced for all usecases would makes heat flows more comprehensive and support the optimisation of heat distribution.

The implementation of a control strategy for heat distribution has to be integrated into the operating strategy of the hybrid vehicle, therefore specific component behavior and interaction will have to be considered as well as optimisation potentials in synergy effect utilisation for transient simulations.

Since some OEMs defined test criteria for hybrid vehicles' cooling systems to guarantee reliability in extreme driving conditions, further development of standardised criteria would enable an evaluation, which should consider component durability, warm up acceleration and component savings besides energy effort for cooling and heating demands, costs of production and vehicle weight.

Appendix A

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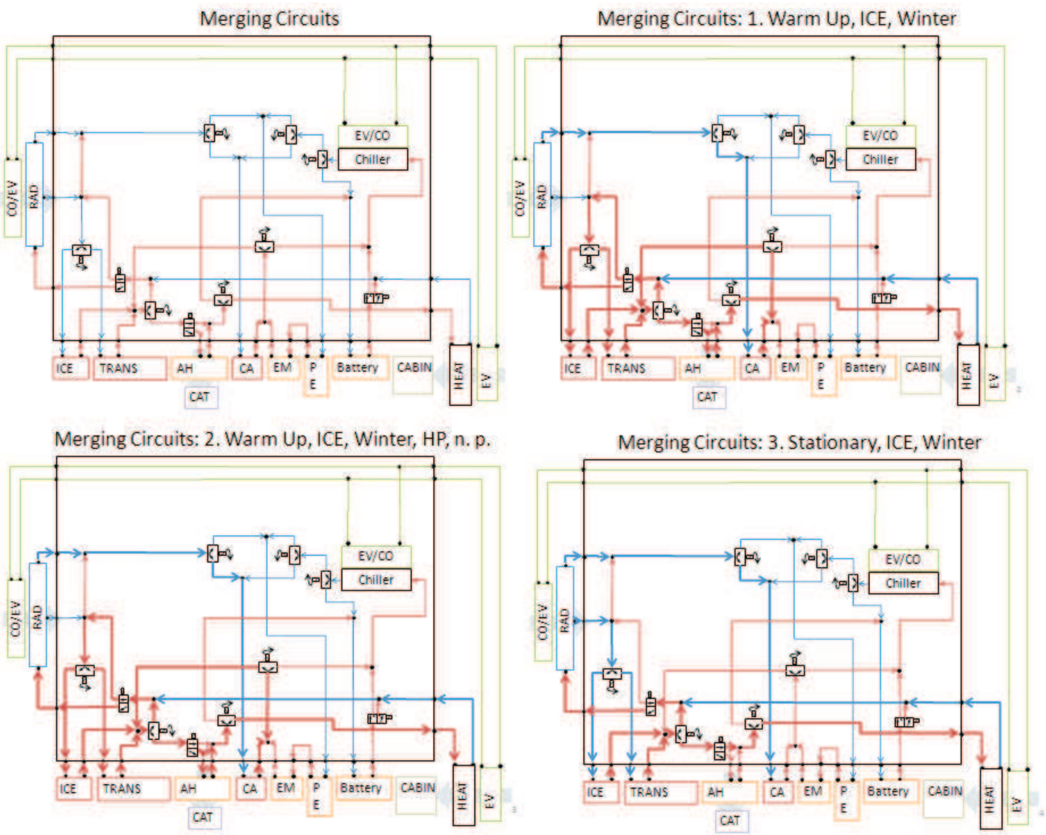
Appendix B

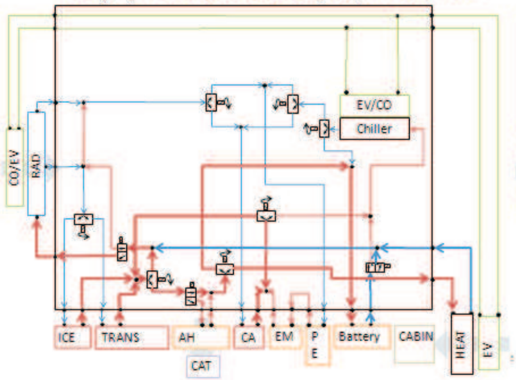
Usecase Heat Flows

For the introduced cooling concept designs the theoretical heat flows are sketched in the following sections.

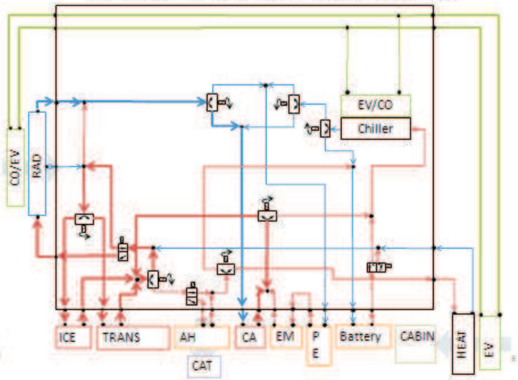
B.1 Concept: Merging Circuits



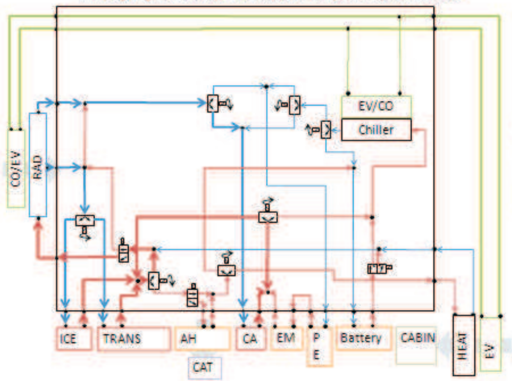
Merging Circuits: 4. Stationary, ICE, Winter, PREP



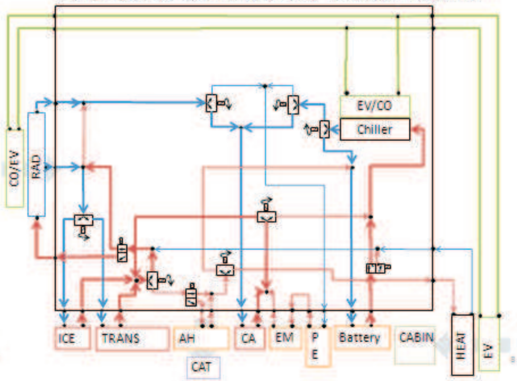
Merging Circuits: 5. Warm Up, ICE, Summer



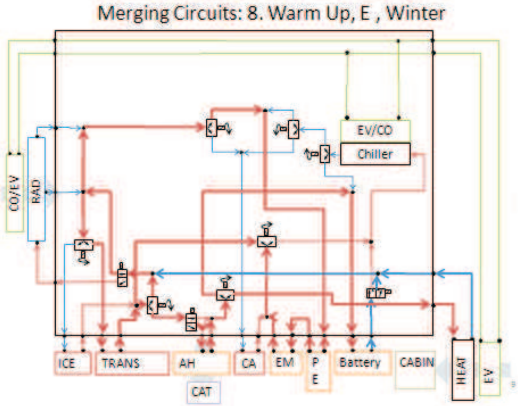
Merging Circuits: 6. Stationary, ICE, Summer



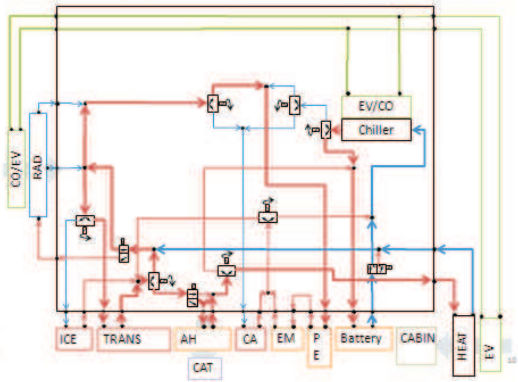
Merging Circuits: 7. Stationary, ICE, Summer, PREP



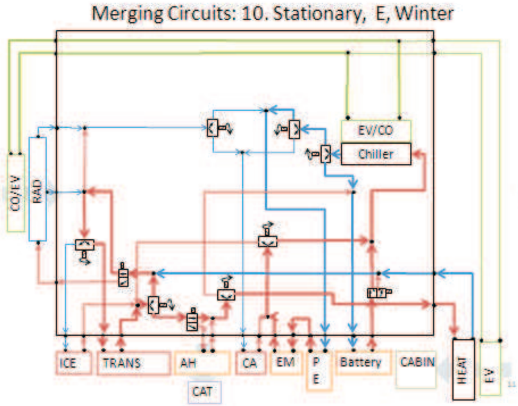
Merging Circuits: 8. Warm Up, E , Winter



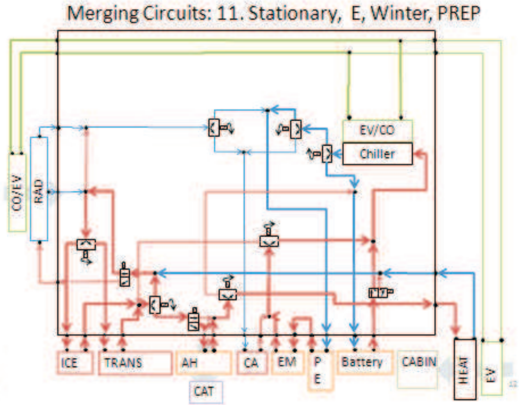
Merging Circuits: 9. Warm Up, E , Winter, HP



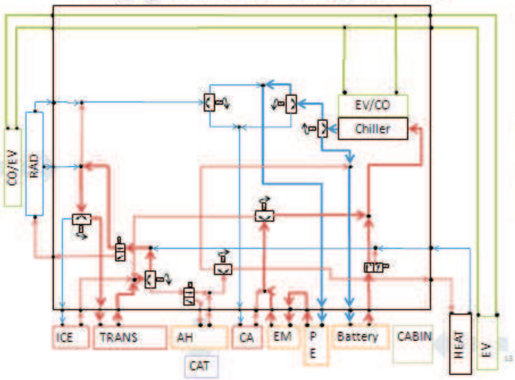
Merging Circuits: 10. Stationary, E, Winter



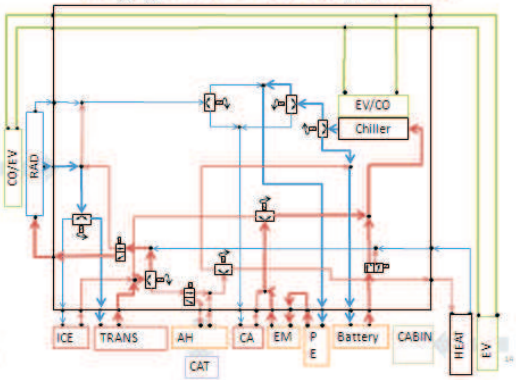
Merging Circuits: 11. Stationary, E, Winter, PREP



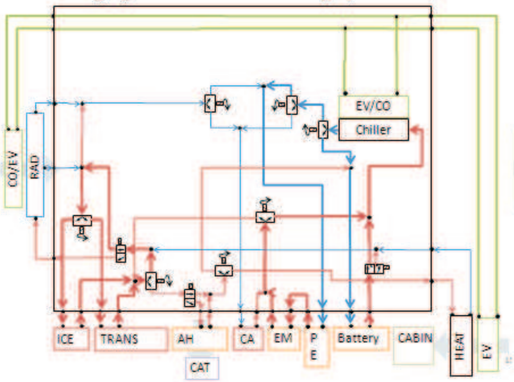
Merging Circuits: 12. Warm Up, E, Summer



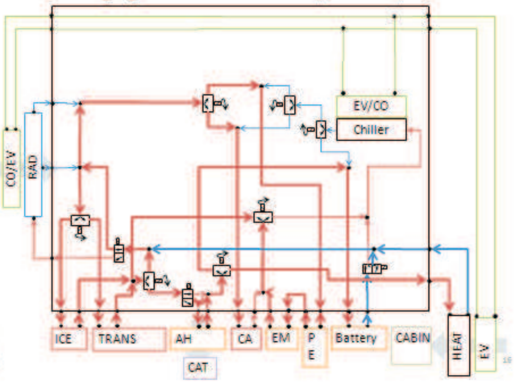
Merging Circuits: 13. Stationary, E, Summer



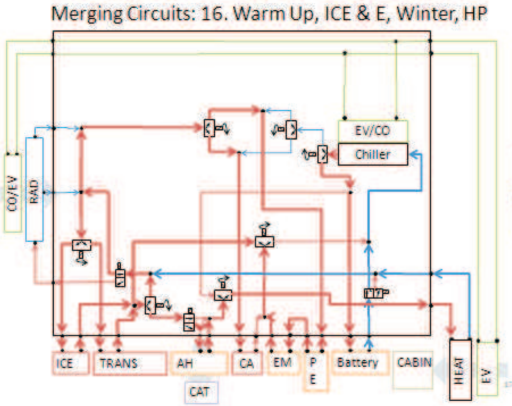
Merging Circuits: 14. Stationary, E, Summer, PREP



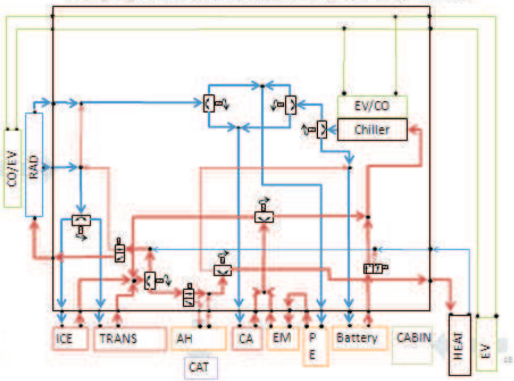
Merging Circuits: 15. Warm Up, ICE & E, Winter



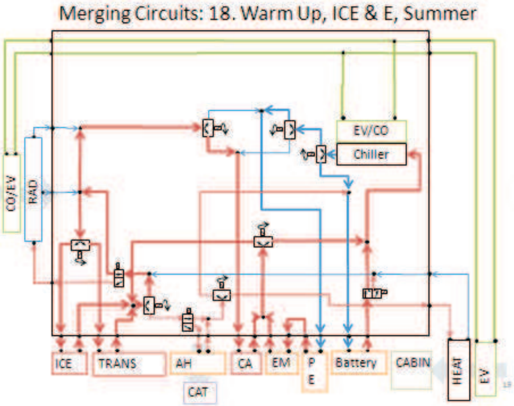
Merging Circuits: 16. Warm Up, ICE & E, Winter, HP



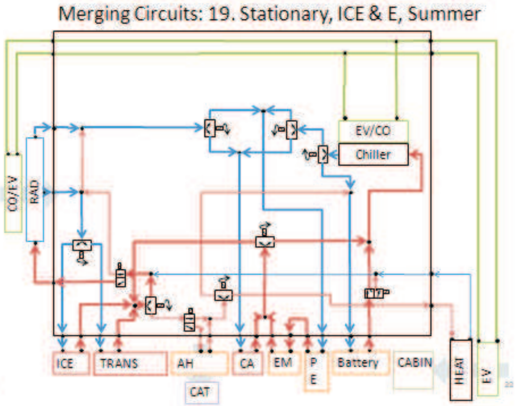
Merging Circuits: 17. Stationary, ICE & E, Winter



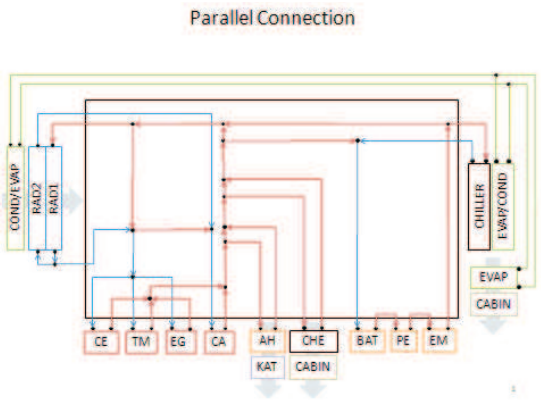
Merging Circuits: 18. Warm Up, ICE & E, Summer

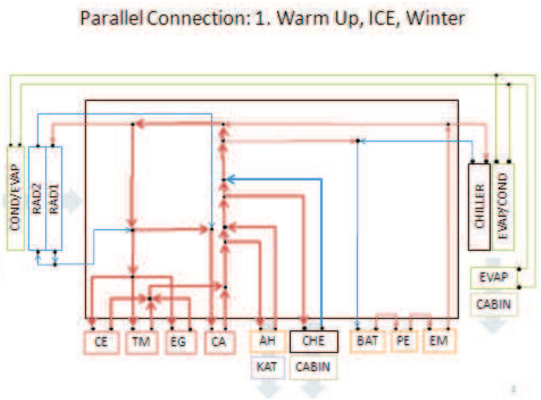


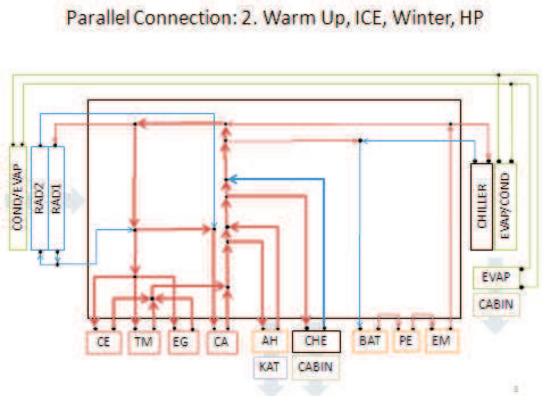
Merging Circuits: 19. Stationary, ICE & E, Summer

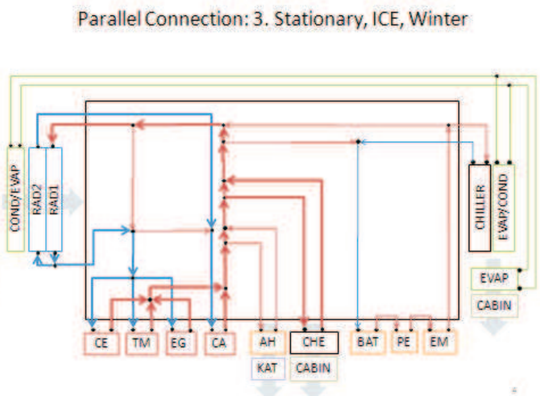


B.2 Concept: Parallel Connection

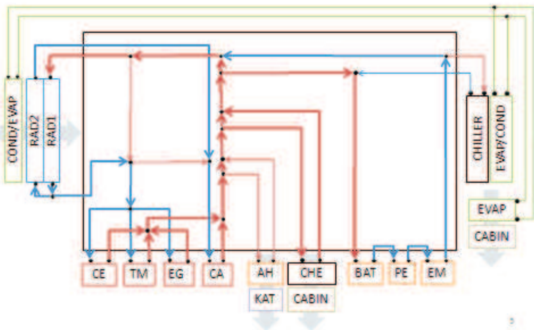




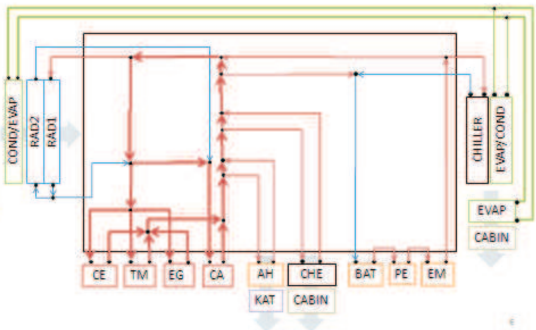




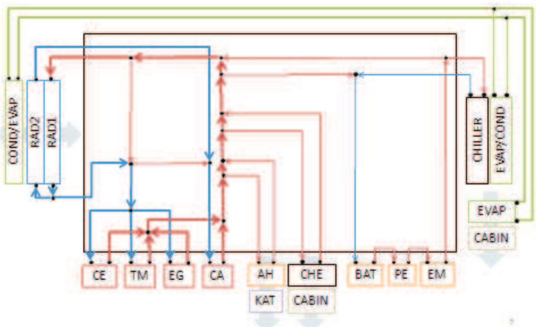
Parallel Connection: 4. Stationary, ICE, Winter, PREP



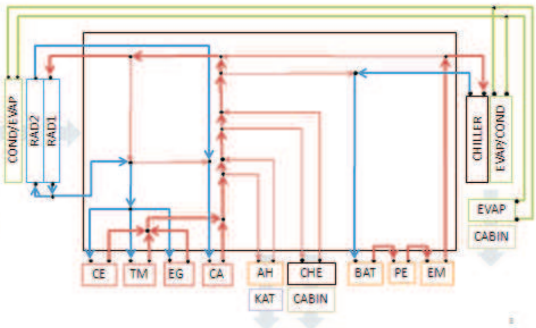
Parallel Connection: 5. Warm Up, ICE, Summer



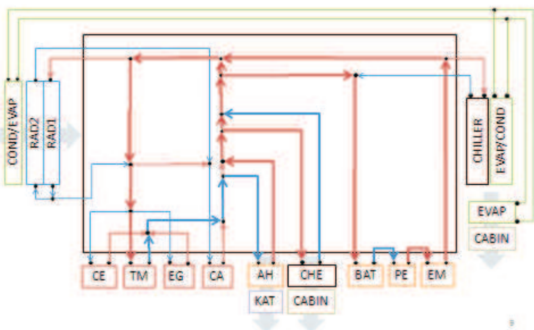
Parallel Connection: 6. Stationary, ICE, Summer



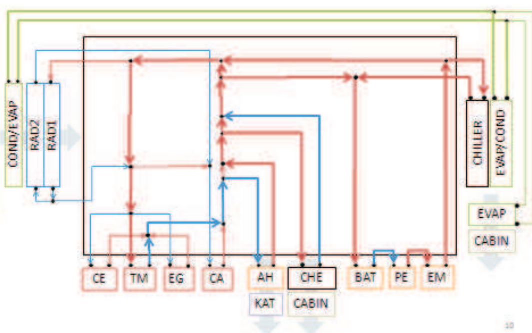
Parallel Connection: 7. Stationary, ICE, Summer, PREP



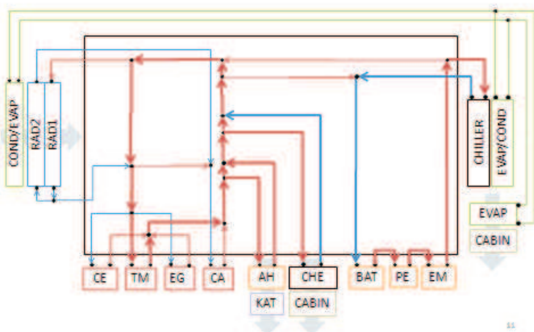
Parallel Connection: 8. Warm Up, E , Winter



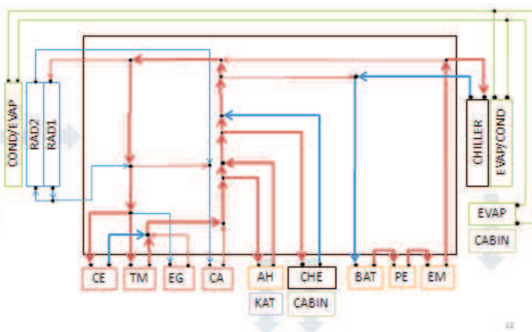
Parallel Connection: 9. Warm Up, E , Winter, HP



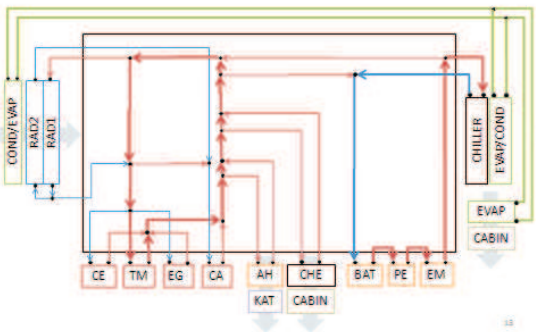
Parallel Connection: 10. Stationary, E, Winter



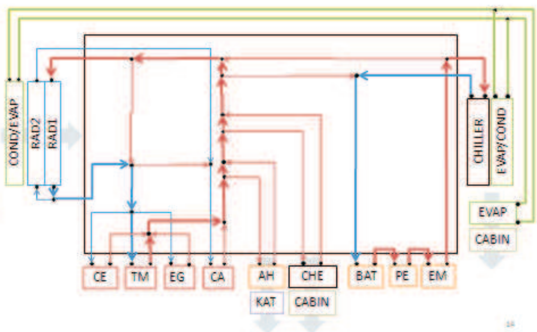
Parallel Connection: 11. Stationary, E, Winter, PREP



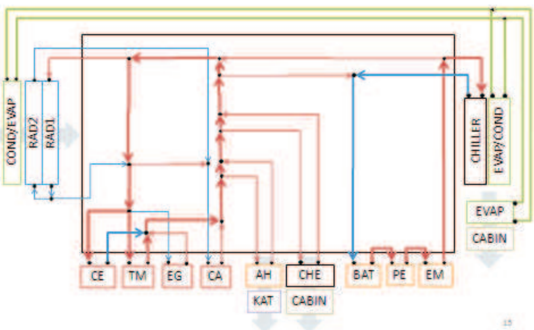
Parallel Connection: 12. Warm Up, E, Summer



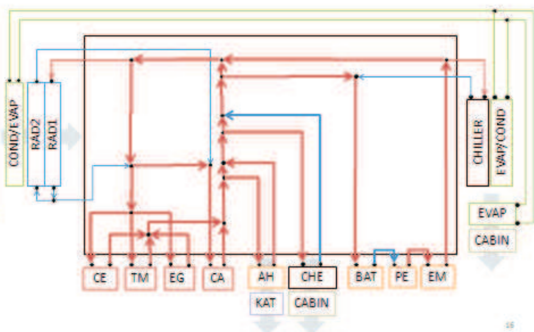
Parallel Connection: 13. Stationary, E, Summer



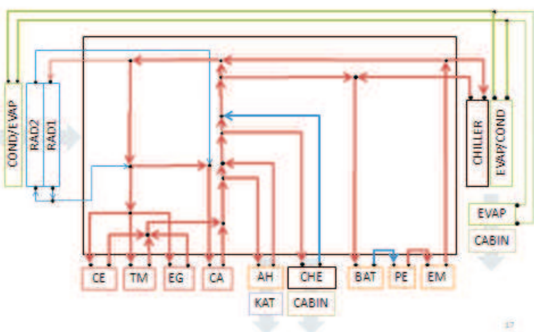
Parallel Connection: 14. Stationary, E, Summer, PREP



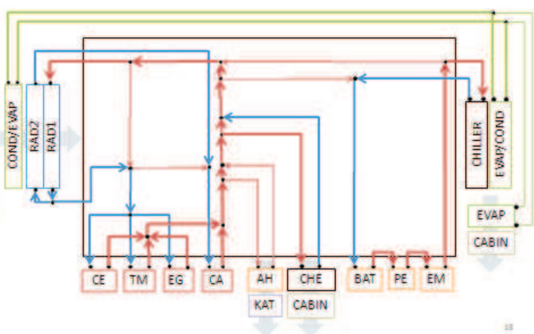
Parallel Connection: 15. Warm Up, ICE & E, Winter



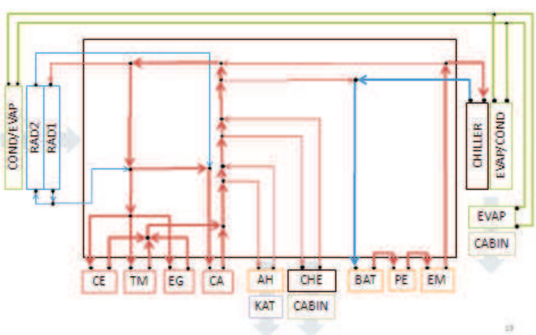
Parallel Connection: 16. Warm Up, ICE & E, Winter, HP



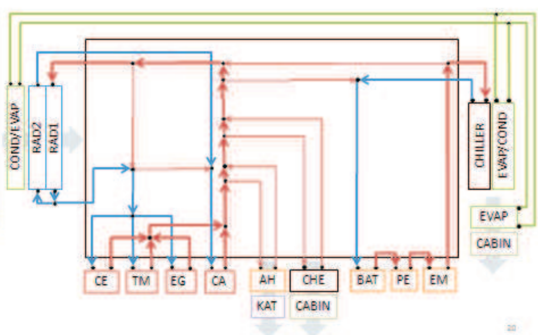
Parallel Connection: 17. Stationary, ICE & E, Winter



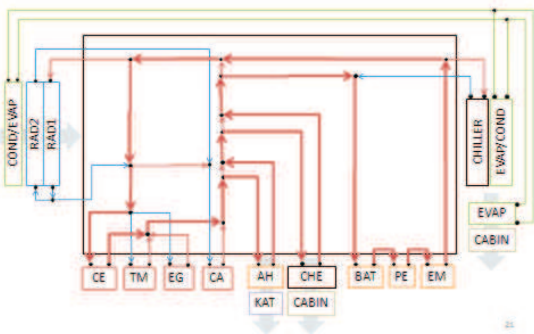
Parallel Connection: 18. Warm Up, ICE & E, Summer



Parallel Connection: 19. Stationary, ICE & E, Summer



Parallel Connection: 20. Preconditioning, ICE & E, Winter



Parallel Connection: 21. Preconditioning, ICE & E, Summer