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Aero

Simulation of a Hydraulic Reservoir Air Pressurization System

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2007-11-05

Technical Note

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19. Kurzfassung In dieser technischen Niederschrift wird die dynamische Simulation eines luftbedruckten Hydraulikreservoirs besprochen. Die Simulation basiert auf einem MATLAB/ Simulink Programm. Das System besteht hauptsächlich aus Druckbegrenzern, Versorgungsrohren, einer RPU (RPU: Reservoir Pressurization Unit), einem Überdruckventil und einem Hydraulikreservoir. Jede Komponente wird durch einen unabhängigen Modelblock beschrieben. Die verschiedenen Strömungswiderstände werden entweder durch analytische Funktionen oder Kennlinien beschrieben. Innerhalb der Versorgungsrohre wird Wärmeübertragung durch die Rohrwand bzw. die Isolation berücksichtigt.		
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19. Abstract This Technical Note describes the dynamical simulation of a reservoir pressurizing system. The simulation is based on a MATLAB/Simulink program. The system consists mainly of restrictors, supply lines, a reservoir pressurization unit, a reservoir relief valve and a hydraulic reservoir. Each component is described by an independent model block. The different flow resistances are based on analytical functions or characteristic maps. Inside the supply lines heat transfer via the duct wall respectively the insulation takes place.		
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1 Introduction

1.1 The Simulation System

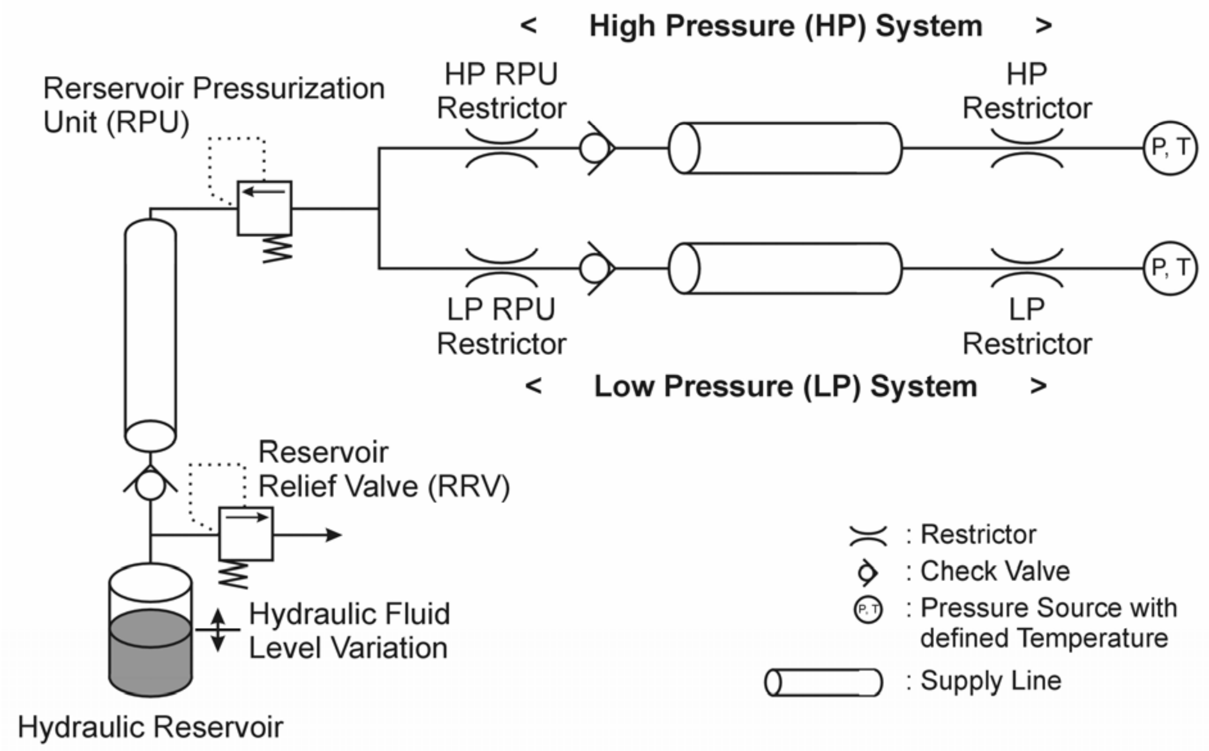


Figure 1 Simulation system

The investigated simulation-system is based on the hydraulic reservoir pressurizing system described in Figure 1. In this system a hydraulic reservoir is pressurized via a high pressure respectively a low pressure system. The boundary limits of the high pressure system can be varying in a range p_{high} = 500000 Pa ... 2000000 Pa and T_{high} = 350 °C ... 550 °C. The ranges of the boundary limits of the low pressure system are p_{low} = 100000 Pa ... 500000 Pa and T_{low} = 150 °C ... 250 °C.

The hydraulic reservoir has an overall volume V_t. The overall volume is split in a volume fraction V_{air}, which is filled by air. The other fraction V_{fluid} is filled by a hydraulic fluid. The behaviour of the overall system due to a variation of the hydraulic fluid level can be investigated with the developed simulation-model. The air pressure inside the reservoir is controlled by pressure maintaining valve (RPU: *Reservoir Pressurization Unit*). The reservoir relief valve *RRV* protects the reservoir against overpressure.

The opening function of the RPU is shown in Figure 2a. The valve is open until a pressure $p_{RPU} = p_{limit} - \Delta p/2$ is reached. The valve is fully closed at the pressure $p_{RPU} = p_{limit} + \Delta p/2$. For the chosen system the opening function of the RPU is most suitable fitted by a pair of variates p_{limit} = 450000 Pa and Δp = 10000 Pa.

The outflow function of the reservoir relief valve (RRV) is shown in Figure 2b. The valve opens at a pressure $p_{reservoir,1}$, $(p_{reservoir,1} - p_{ambient}) - p_{limit,1}$. At the pressure $p_{reservoir,2}$, $(p_{reservoir,2} - p_{ambient}) - p_{limit,2}$ the valve is fully open and a maximum mass flow of 0.00267 kg/s leaves the reservoir. For the simulated system a adequate pair of variates of $p_{limit,1}$ = 550000 Pa and $p_{limit,1}$ = 625000 Pa can be used. The ambient conditions $p_{ambient}$ and $T_{ambient}$ can be varying in a range between 0.2 Pa ... 1.2 Pa and -55 °C ... 90 °C.

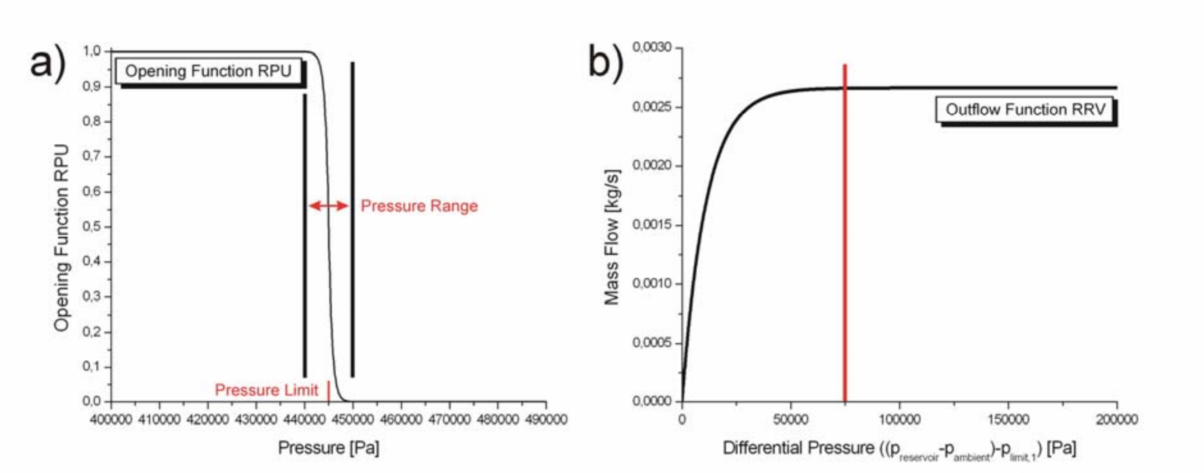


Figure 2 a) The opening function of the reservoir pressurization unit (RPU) (see Figure 1).
b) The outflow-function of the reservoir relief valve (RRV) (see Figure 1)

The pressure drop over the RPU is limited by the RPU-restrictors. For each pressure system one independent restrictor is used. These restrictors are described by measured characteristic maps. Using characteristic maps in a form shown in Figure 3a at a certain mass flow value the pressure difference over the restrictor can be determined. For the simulation model characteristic maps in a transposed form have to be used (see Figure 3b). In this way the RPU-restrictors can be defined as flow resistances and at a given pressure drop the mass flow through the restrictor can be determined.

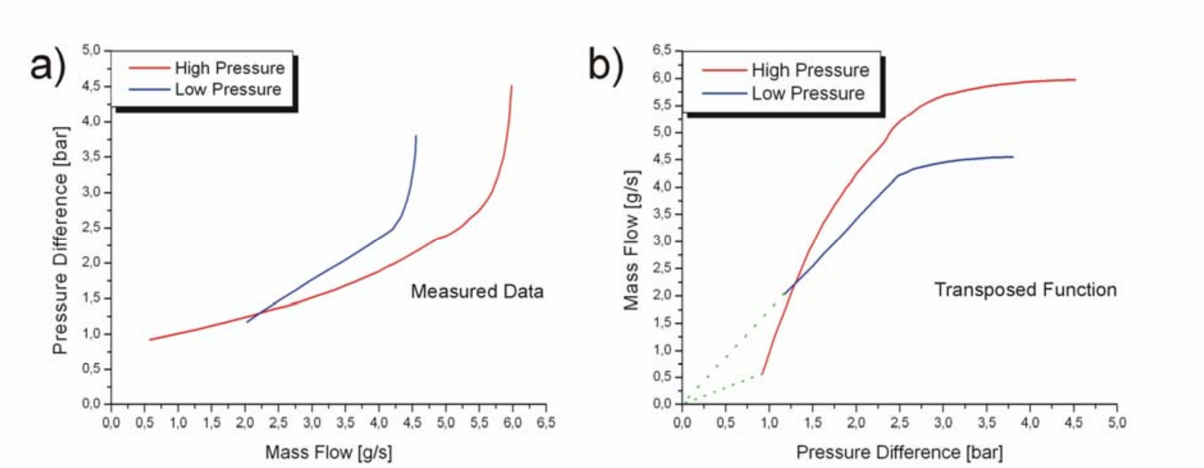


Figure 3 a) The measured characteristic maps of the used RPU HP (—) and LP restrictors (—) (see Figure 1).
b) The transposed characteristic maps

1.2 Mode of Operation of MATLAB/Simulink

Each component (see Figure 1) is related to an independent Simulink block. Each block can be parameterized by a specific input mask (see Figure 4). The input parameters are divided in parameters, which describe the component itself, and initial parameters, which are related to the different state variables of the system.

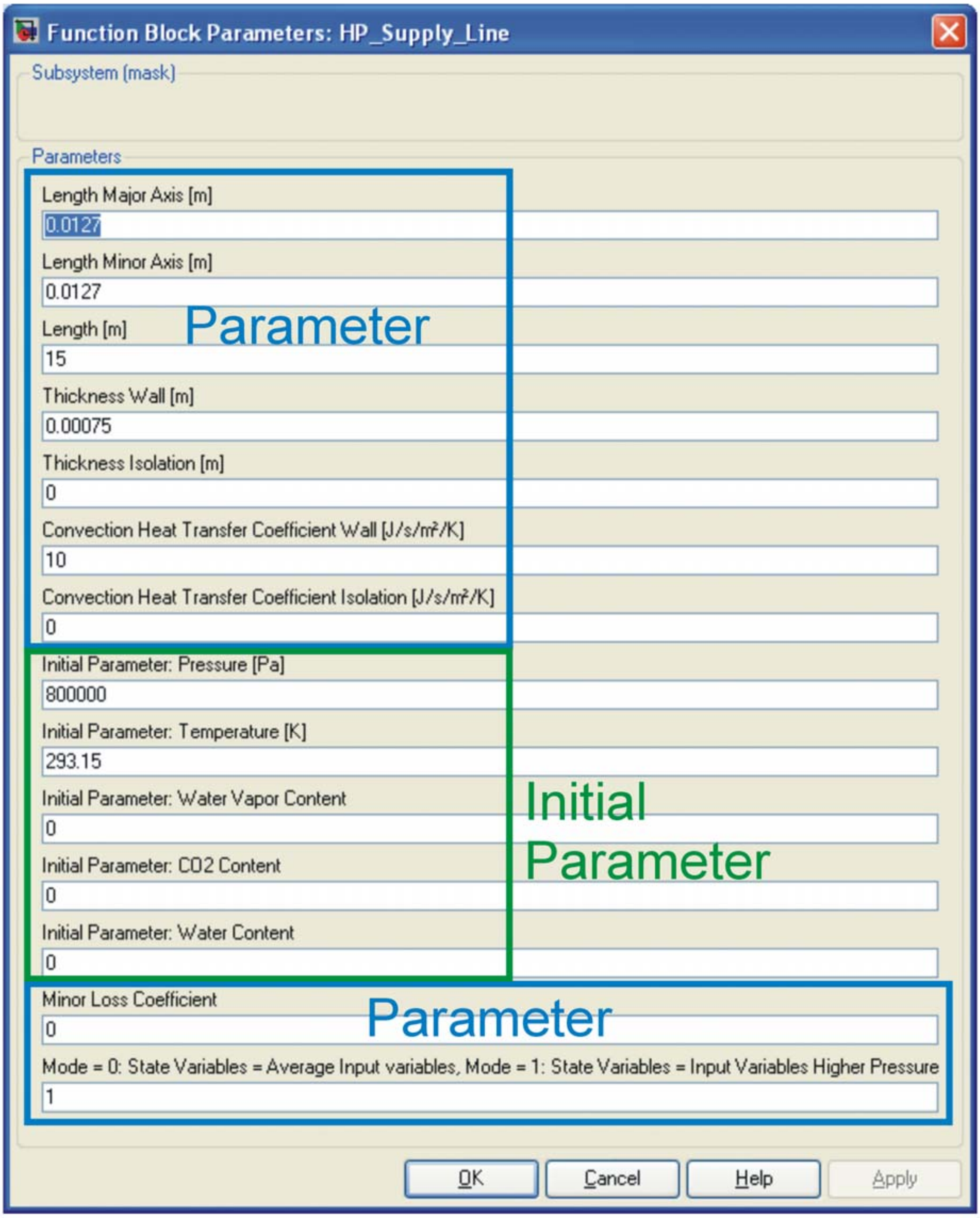


Figure 4 Input mask of the high pressure supply line.

The interaction between different Simulink blocks is correlated to a so-called feedback structure. Each block needs the information of the different state variables of its neighboring block (see Figure 5b). Via the inputs of each block, information is transferred to the block, and via the outputs, information is transferred to other blocks. The Simulink inputs respectively the outputs are not strictly correlated to physical in- and outputs (see Figure 5a).

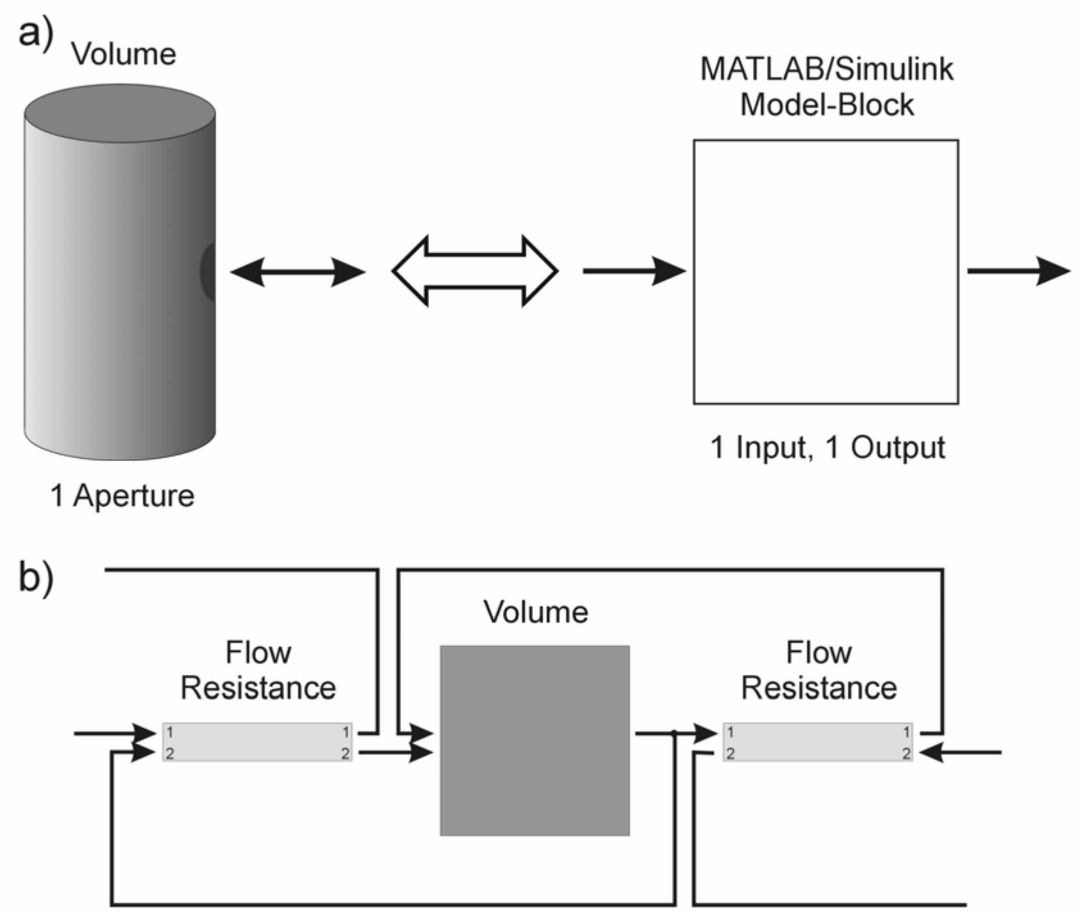


Figure 5 a) Differentiation between a real component and a MATLAB/Simulink model-block.
b) Feedback structure of a Simulink model

The inner structure of MATLAB/Simulink is combined with the characterization of time-dependant systems. At each time-step *dt* within a certain time-range *Δt* the states of the simulated system are calculated. The state of the system is specified by a set of state variables. The set of state variables is related to a set of state equations (see Figure 6).

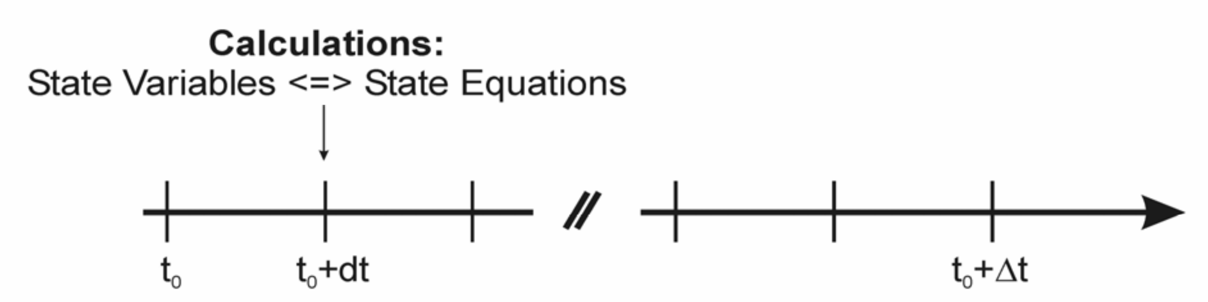


Figure 6 The inner structure of an MATLAB/Simulink system.

Three types of state equations can be distinguished. The time-dependant rate equations (see Equation 1).

$$\frac{dy(t)}{dt} = f(y(t);t) \tag{1}$$

In general f(y(t);t) is not only function of y(t), but also a function of other time-dependant variables. Equations according to form Equation 1 are solved by an integrator (see Equation 2).

$$y_i = \sum_{j=1}^{i-1} dy_j + \underbrace{\left[\int_{t_0+(i-1)\cdot dt}^{t_0+i\cdot dt} f(y_{(i-1)}(t);t)\cdot dt \right]}_{dy_i} + y_{Init}\ , i = 1...N, \Delta t = N\cdot dt, dy_0 = 0 \tag{2}$$

Equation 2 is only solvable, if the initial parameter for each state variable is known. The second type of state equations is a quasi stationary equation (see Equation 3).

$$y(t) = f(t) \tag{3}$$

These Equations are solvable without any knowledge of initial parameters. The third type of equations is the steady state type (see Equation 4).

$$y(t) = y = Const \tag{4}$$

The integrator in Equation 2 is an intrinsic function block of MATLAB/Simulink. The functionality of the integrator is associated to the chosen solver mode. The solver function defines the step size *dt* and the algorithm of integration. MATLAB/Simulink makes available two different solver species. A fixed step solver and a variable step solver. For the developed simulation model the fixed step solver ode4 with a step size of 0.0001s based of a Runge-Kutta algorithm shows the best performance.

1.3 Physical Description

The developed simulation model is based of three different component classes. At first general and specialized flow resistances, generalized volumes and heat resistances. The different state equations are derived by thermodynamical, mechanical and heat transfer aspects.

1.3.1 Flow Resistances

The components of the class of flow resistance have to be distinguished in general and specialized components.

The generalized components can be described by a parameter set and an analytical function. The specialized components can be described by characteristic maps. As input the flow resistance requires pressure, density and temperature. The output of the flow resistance is the mass flow

Knowing the pressure drop the mass flow through the flow resistance can be calculated. Under assumption, that incompressible flow properties are fulfilled, the outflow equation of form 1 (see Equation 5) has to be used. This type of flow resistance can be used to specify the flow properties of ducts, e.g. the flow properties of the different supply lines within the simulation-model

$$
\begin{aligned}
v &= \sqrt{\Delta p \cdot \frac{2}{\rho} \cdot \frac{1}{\frac{L}{D} \cdot \lambda(Re(v)) + \zeta}} \\
\dot{m}(t) &= A \cdot \rho \cdot v \\
Re(v) &= \frac{v \cdot D \cdot \rho}{\eta}
\end{aligned}
\tag{5}
$$

A is the cross section of the flow resistance. The equation Equation 5 has an initialization problem. Calculating the velocity *v* the Reynolds-number Re has to be known. An iterative loop is used to solve this problem. Density respectively temperature inside the resistance can be calculated by the average of the input values (*Mode 0*), or are defined by the values of the input with the highest pressure (*Mode 1*)

Systems, which can't be described by incompressible flow resistances, can be simulated with elements, which are based on compressible outflow functions (see Equation 6).

$$
\dot{m} = \frac{A \cdot p_T}{\sqrt{T_T}} \cdot \sqrt{\frac{\kappa}{R_i}} \cdot M \cdot \left(1 + \frac{\kappa - 1}{2} M^2\right)^{-\frac{\kappa+1}{2\cdot(\kappa-1)}} \tag{6}
$$

The mass flow is a function of the Mach number M inside the system. Total pressure respectively total temperature is always defined by the input with the highest pressure. The state of the out flowing air is described by the isentropic state equations (see Equation 7).

$$\frac{p}{p_T} = (\frac{\rho}{\rho_T})^{\kappa} = (\frac{T}{T_T})^{\frac{\kappa}{\kappa-1}} \tag{7}$$

$\kappa = c_p/c_V$ is the ratio of the specific heat capacities by constant pressure c_p respectively constant volume c_V. On the basis of the fact, that the Mach number M such as the mass flow is a function of the flow velocity, the algorithm based on Equation 6 shows an initialization problem. There is a lack of a convergent iterative loop. Therefore the equation Equation 6 has to be solved approximately for three different regimes (see Equation 8a …c). R is the specific gas constant of the air mixture.

Subsonic Regime: $p/p_T > 0.53$

$$\dot{m} = \frac{A \cdot p_T}{\sqrt{T_T}} \cdot \sqrt{\frac{2\,\kappa}{(\kappa-1)\,R}\left(\left(\frac{p}{p_T}\right)^{2/\kappa} - \left(\frac{p}{p_T}\right)^{\kappa+1/\kappa}\right)} \tag{8a}$$

Sonic Regime: $p/p_T < 0.53$

$$\dot{m} = \frac{A \cdot p_T}{\sqrt{T_T}} \cdot \sqrt{\frac{\kappa}{R}\left(\frac{2}{\kappa+1}\right)^{\kappa+1/\kappa-1}} \tag{8b}$$

Transsonic Regime: $M > 1$ (see Equation 6)

$$v = \sqrt{\Delta p \cdot \frac{2}{\rho_{FR}}}$$
$$M = \frac{v}{\sqrt{\kappa \cdot \mathrm{R_i} \cdot T}} \tag{8c}$$

In the case of specialized flow resistance the mass flow is calculated by a characteristic map.

1.3.2 Generalized Volume

The generalized volume needs as input mass flow and temperature. Based on the enthalpy equation (see Equation 9), the differential form of the enthalpy can be written in following way (see Equation 9). The difference of the potential energy and the kinetic energy of the start and end state of a system can be neglected.

$$H = U + p \cdot V$$
$$\rightarrow \frac{dH}{dt} = (Q_{dot} + H_{dot,in,out}) + V\frac{dp}{dt} + \underbrace{[p\frac{dV}{dt}]}_{0} \qquad (9)$$

A mass flow $\dot{m}_{in}$ with the temperature T_{in} and a specific heat capacity $c_{p,in}$ enters the system and a gas flow defined by a mass flow $\dot{m}_{out}$ leaves the system. Under this assumption $\dot{H}_{in,out}$ can be written, according Equation 10. The temperature T and the specific heat capacity c_p of the outgoing flow are defined by the gas mixture inside the volume.

$$\dot{H}_{in,out} = \dot{m}_{in} \cdot c_{p,in} \cdot T_{in} - \dot{m}_{out} \cdot c_p \cdot T \qquad (10)$$

For a volume with a constant volume value, the differential equations (see Equation 11) for temperature, density and pressure can be derived with help of the ideal gas law and the mass balance of the system.

$$\begin{aligned} \frac{dT}{dt} &= \frac{1}{V \cdot \rho \cdot c_v}(\dot{Q} + \dot{H}_{in,out}) - \frac{T}{\rho} \cdot \frac{d\rho}{dt} \\ \frac{d\rho}{dt} &= \frac{1}{V} \cdot \frac{dm}{dt} = \frac{\dot{m}_{in} - \dot{m}_{out}}{V} \\ \frac{dp}{dt} &= R_i \cdot \rho \cdot \frac{dT}{dt} + R_i \cdot T \cdot \frac{d\rho}{dt} \end{aligned} \qquad (11)$$

For a volume with a non constant volume value, the variation of the volume has to be considered. Within a time step the volume changes from a value V to a value V'. In the case, that $V'<V$ the gas inside the volume is compressed. In the case, that $V'>V$ expansion takes place.

For a non constant volume at first the differential equation in form of Equation 11 will be calculated. After the integration step the new density $\rho' = m/V'$ due to the volume change is computed. Using the density ρ' and the equation Equation 7, the new values of the temperature T' and the pressure p' can be calculated.

1.3.3 Heat Transfer

The supply lines are a combination of an incompressible flow resistance and a generalized volume. Inside the supply line heat transfer via the duct wall and the insulation takes place between the air and the surrounding area.

Knowing the flow velocity respectively the Reynolds number, the Nusselt number respectively convection heat transfer coefficient the can be calculated using equation Equation 12.

$$\begin{aligned}
Nu &= (3.66^3 + 1.66^3 \ \mathrm{Re} \ \mathrm{Pr} \ \frac{D_{duct}}{L_{duct}})^{1/3}, \text{Laminar Flow} \\
Nu &= 0.012 \ (\mathrm{Re}^{0.87} - 280) \ \mathrm{Pr}^{0.4} \ (1 + \frac{D_{duct}}{L_{duct}})^{2/3}, \text{Turbulent Flow} \\
\mathrm{Pr} &= \frac{\eta_{air} \ c_{p,air}}{\lambda_{air}} \\
Nu &= \frac{\alpha_{air} \ D_{duct}}{\lambda_{air}}
\end{aligned} \tag{12}$$

The Prandtl number Pr is a relation of the viscosity η, the specific heat capacity c_p and the thermal conductivity λ. The Nusselt number Nu is a relation of the convection heat transfer coefficient α, the Diameter of the duct D_{duct}. The thermal conductivity is a function of the air temperature T.

The overall heat transfer can be computed by equation Equation 13. The convection heat transfer coefficient of the wall and the insulation are user defined parameters.

$$\dot{Q}_{air,ambient} = \frac{A_{wall} \ (T - T_{ambient})}{(1/\alpha_{air}) + (1/\alpha_{wall}) + (1/\alpha_{isolation})} \tag{13}$$

2 Description of the Components

The simulation-system is shown in Figure 7. The different model-blocks are described in the following sections.

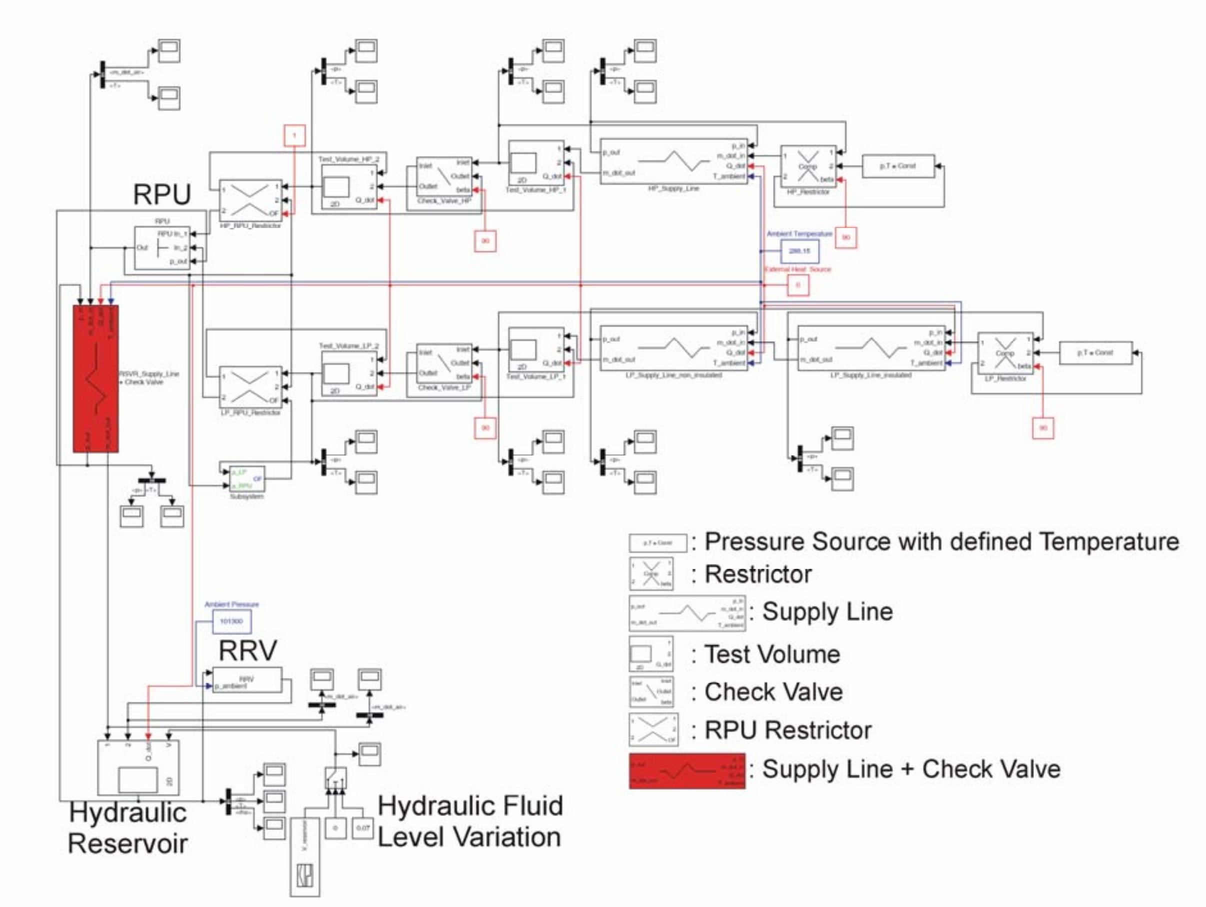


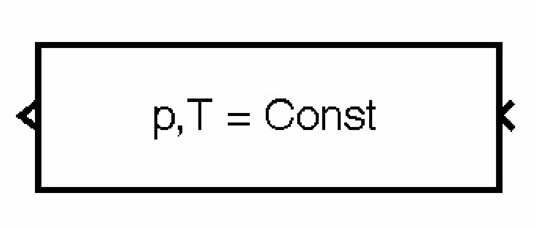
Figure 7 Simulink simulation model

2.1 Pressure Source with Defined Temperature

Component Name: Pressure Source with defined Temperature

Component Class: Constant Block

Symbol:



Parameters:

Pressure [Pa]	p
Temperature [K]	T
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Number of Inputs: 1

Number of Outputs: 1

Output Variables:

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Mass Dry Air [kg]	$m_{air} = 0$
Mass Flow Dry Air [kg/s]	$\dot{m}_{air} = 0$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content:	$x_{H2O,liq}$

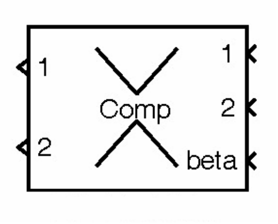
Description: Pressure, temperature, water vapor content, CO_2 content and water content are given as constants. Using the ideal gas law the density can be calculated.

2.2 Restrictor

Component Name: HP Restrictor, LP Restrictor

Component Class: Generalized Flow Resistance - Quasi Stationary Block

Symbol:



Parameters:	Surface [m²]	A
	Minor Loss Coefficient	ζ

Number of Inputs: 3

Input Variables (*1 + 2*):	Pressure [Pa]	p
	Density [kg/m³]	ρ
	Temperature [K]	T
	Water Vapor Content	$x_{H2O,gas}$
	CO_2 Content	x_{CO2}
	Water Content	$x_{H2O,liq}$

Input Variables (*beta*):	Opening Angle [°]	β

Number of Outputs: 2

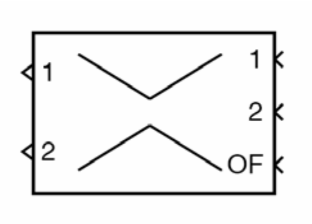
Output Variables (*1 + 2*):	Pressure [Pa]	p
	Density [kg/m³]	ρ
	Temperature [K]	T
	Mass Dry Air [kg]	$m_{air} = 0$
	Mass Flow Dry Air [kg/s]	$\dot{m}_{air}$
	Water Vapor Content	$x_{H2O,gas}$
	CO_2 Content	x_{CO2}
	Water Content	$x_{H2O,liq}$

Description: The mass flow is calculated with help of the compressible mass flow equation (see Equation 6, 8). The gas is described by the isentropic state equation (see Equation 17).

Component Name: HP RPU Restrictor, LP RPU Restrictor

Component Class: Specialized Flow Resistance - Quasi Stationary Block

Symbol:



Parameters: Characteristic Map $\Delta p \rightarrow \dot{m}_{air}$

Number of Inputs: 3

Input Variables (*1 + 2*):

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Input Variables (*OF*):

Opening Factor	OF

Number of Outputs: 2

Output Variables (*1 + 2*):

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Mass Dry Air [kg]	$m_{air} = 0$
Mass Flow Dry Air [kg/s]	$\dot{m}_{air}$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

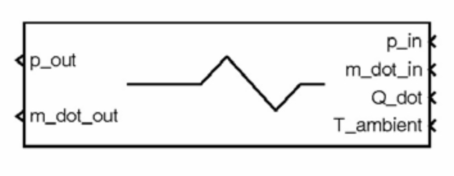
Description: The mass flow is calculated with help of a characteristic Map (see Figure 3). The gas is described by the isentropic state equation (see Equation 7).

2.3 Supply Line

Component Name: Supply Line

Component Class: Generalized Flow Resistance, Generalized Volume, Heat Transfer Unit - Dynamic Block, Quasi Stationary Block

Symbol:



Parameters:

Length Major Axis [m]	D_{major}
Length Minor Axis [m]	D_{minor}
Length [m]	L
Thickness Wall [m]	b_{wall}
Thickness Isolation [m]	$b_{isolation}$
Convection Heat Transfer Coefficient Wall [W / m^2 K]	α_{wall}
Convection Heat Transfer Coefficient Isolation [W / m^2 K]	$\alpha_{isolation}$
Minor Loss Coefficient	ζ
Initial Parameters:	
Pressure [Pa]	p_{init}
Temperature [K]	T_{init}
Water Vapor Content	$x_{H2O,gas,init}$
CO_2 Content	$x_{CO2,init}$
Water Content	$x_{H2O,liq,init}$

Number of Inputs: 4

Input Variables (p_{in}):

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Input Variables ($m_{dot,in}$):

Temperature [K]	T
Mass Flow Dry Air [kg/s]	$\dot{m}_{air}$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Input Variables (Q_{dot}):

External Heat Load [W]	$\dot{Q}$

Input Variables ($T_{ambient}$):

Ambient Temperature [K]	$T_{ambient}$

Number of Outputs: 2

Output Variables (p_{out}):

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Mass Dry Air [kg]	m_{air}
Mass Flow Dry Air [kg/s]	$\dot{m}_{air} = 0$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Output Variables ($m_{dot.out}$):

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Mass Dry Air [kg]	$m_{air} = 0$
Mass Flow Dry Air [kg/s]	$\dot{m}_{air}$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

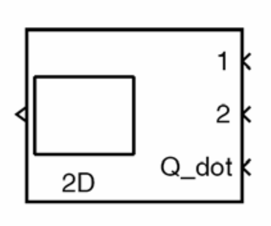
Description: The supply line is a combination of a flow resistance and a generalized volume. The heat transfer via the duct wall and the insulation takes place between the air and the surrounding area. The mass flow is calculated with help of the incompressible mass flow equation (see Equation 5).

2.4 Test Volume/Reservoir

Component Name: Test Volume, Reservoir

Component Class: Generalized Volume - Dynamic Block

Symbol:



Parameters:

Volume	V
Initial Parameters:	
Pressure [Pa]	p_{init}
Temperature [K]	T_{init}
Water Vapor Content	$x_{H2O,gas,init}$
CO_2 Content	$x_{CO2,init}$
Water Content	$x_{H2O,liq,init}$

For a system with a non-constant volume the parameter V is a initial value.

Number of Inputs: 3

Input Variables (*1*+*2*):

Temperature [K]	T
Mass Flow Dry Air [kg/s]	$\dot{m}_{air}$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Input Variables (Q_{dot}):

External Heat Load [W]	$\dot{Q}$

Number of Outputs: 2

Output Variables (*1+2*):

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Mass Dry Air [kg]	m_{air}
Mass Flow Dry Air [kg/s]	$\dot{m}_{air} = 0$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

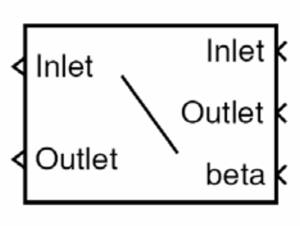
Description: The generalized volume is described by the set of equations Equation 11.

2.5 Check Valve

Component Name: Check Valve

Component Class: Generalized Flow Resistance – Quasi Stationary Block

Symbol:



Parameters:

Surface [m²]	A
Minor Loss Coefficient	ζ

Number of Inputs: 3

Input Variables (*Inlet*+*Outlet*):

Pressure [Pa]	p
Density [kg/m³]	ρ
Temperature [K]	T
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Input Variables (*beta*):

Opening Angle [°]	β

Number of Outputs: 2

Output Variables (*Inlet*+*Outlet*):

Temperature [K]	T
Mass Flow Dry Air [kg/s]	$\dot{m}_{air}$
Water Vapor Content	$x_{H2O,gas}$
CO_2 Content	x_{CO2}
Water Content	$x_{H2O,liq}$

Description: The mass flow is calculated with help of the following equation:

$$v = \sqrt{\Delta p \cdot \frac{2}{\rho_{FR}}}, \dot{m} = A\ \rho\ v$$

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Appendix: Simulation Results

Test Case 1

Boundary limits:
High Pressure System: $p = 20\ 10^5$ Pa $T = 823.15$ K = 550°C
High Pressure System: $p = 5\ 10^5$ Pa $T = 523.15$ K = 250°C

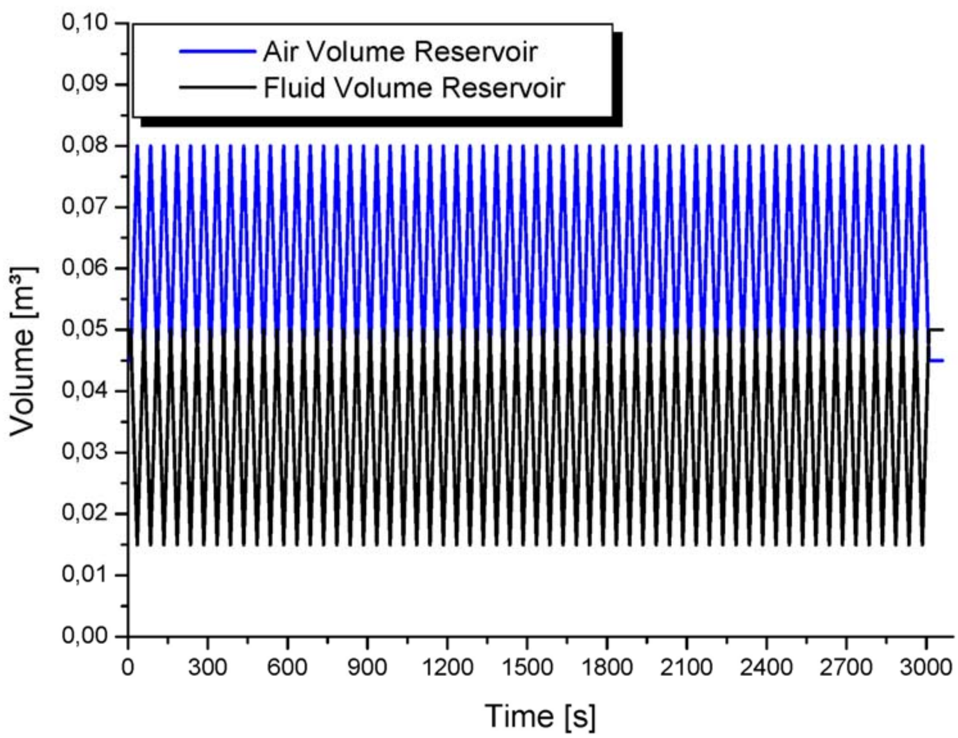
Ambient Conditions: $p = 1.013\ 10^5$ Pa $T = 288.15$ K = 15°C

Simulation Time: $\Delta t = 3060$s

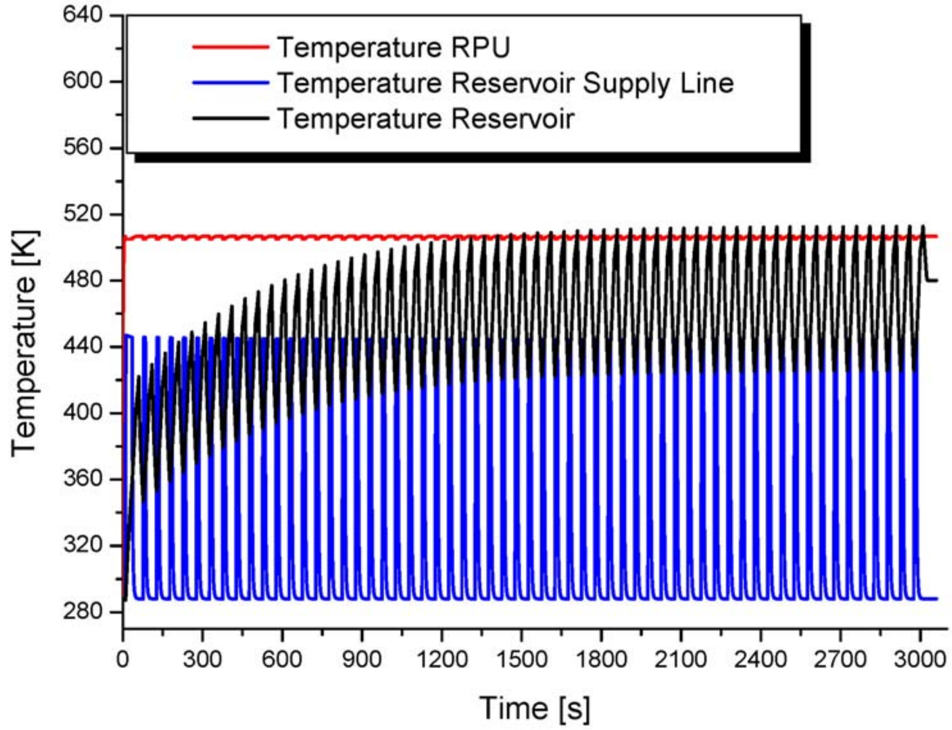
Time Step: $dt = 0.0001$s

Solver Type: ode4 (Runge-Kutta)

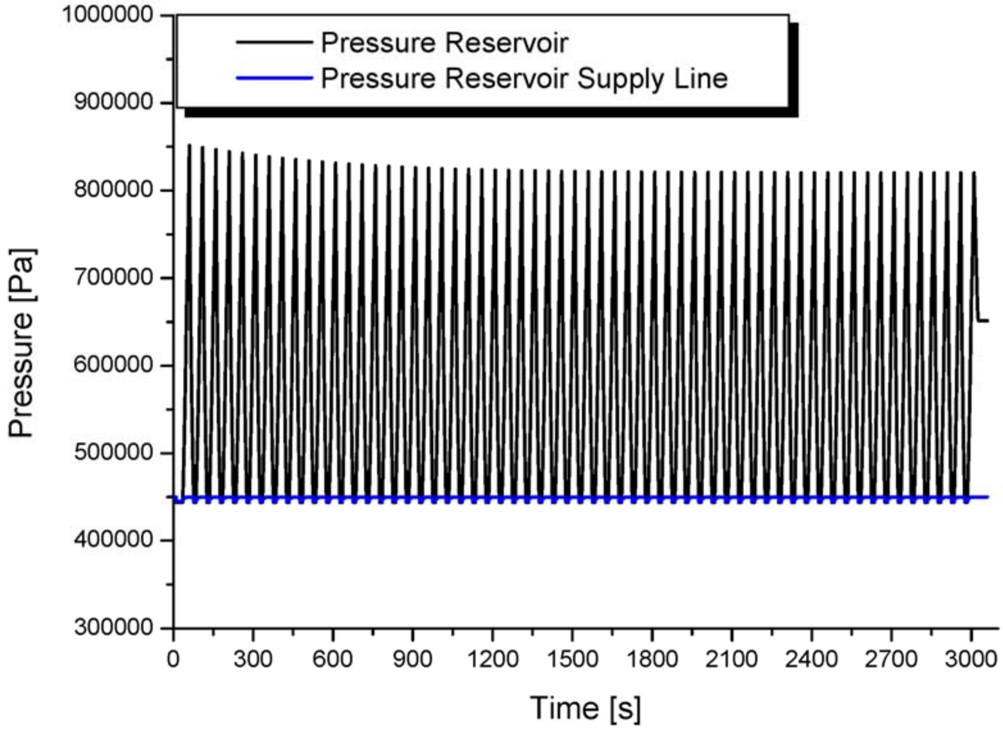
Hydraulic Fluid Level Variation:



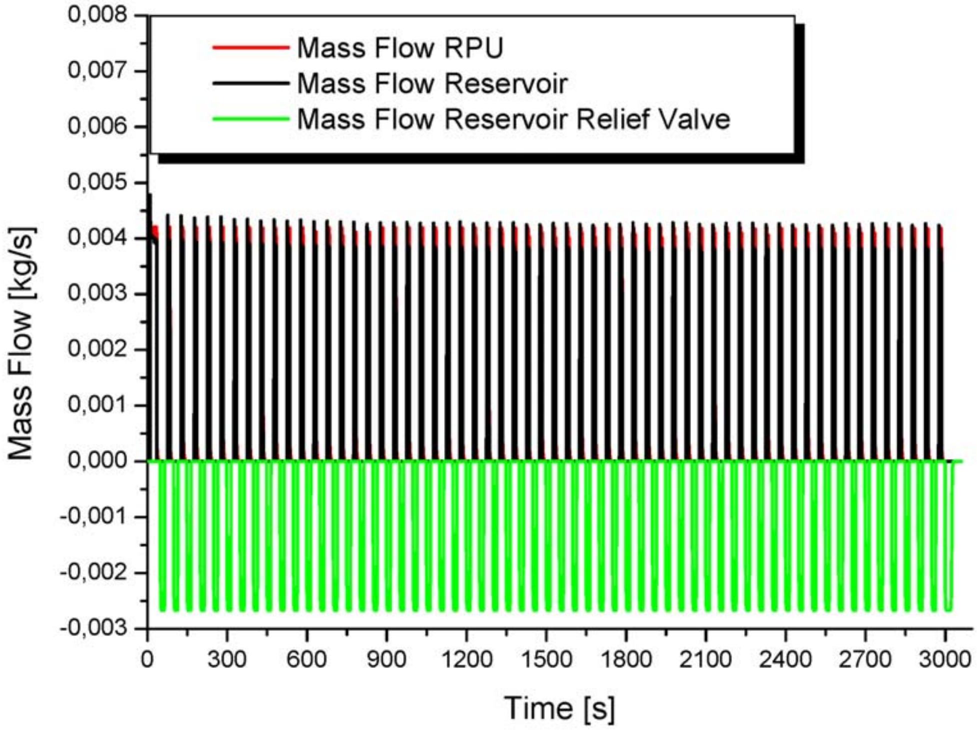
Temperature Profiles:



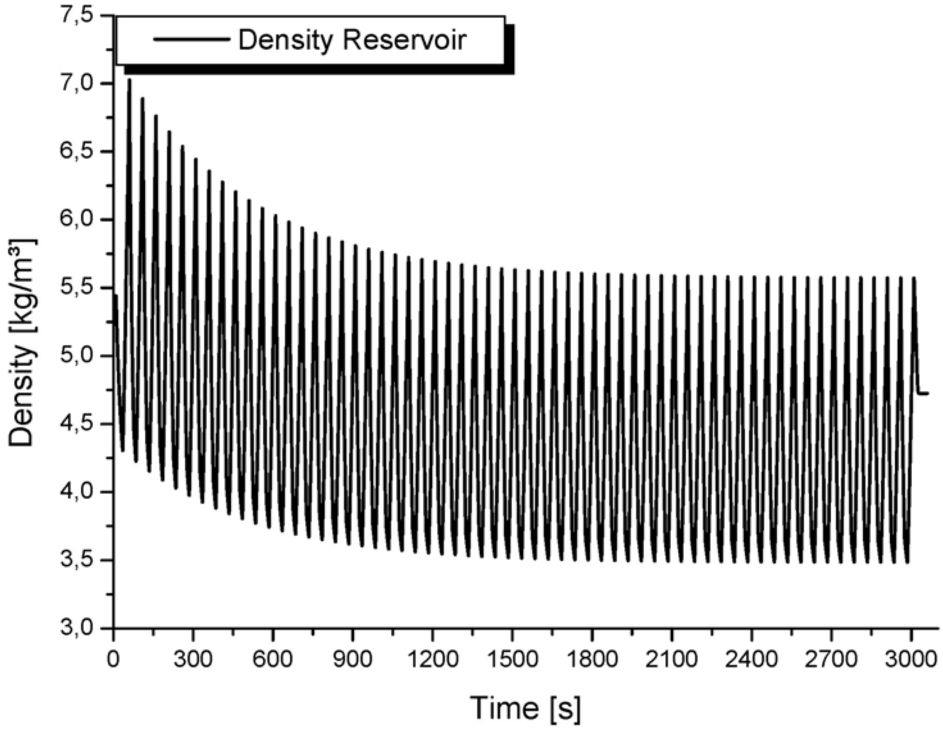
Pressure Distributions:



Mass Flow Distributions:



Density Reservoir:



Test Case 2

Boundary limits:

High Pressure System: $p = 5\ 10^5$ Pa $T = 623.15$ K = 350°C

High Pressure System: $p = 1\ 10^5$ Pa $T = 423.15$ K = 150°C

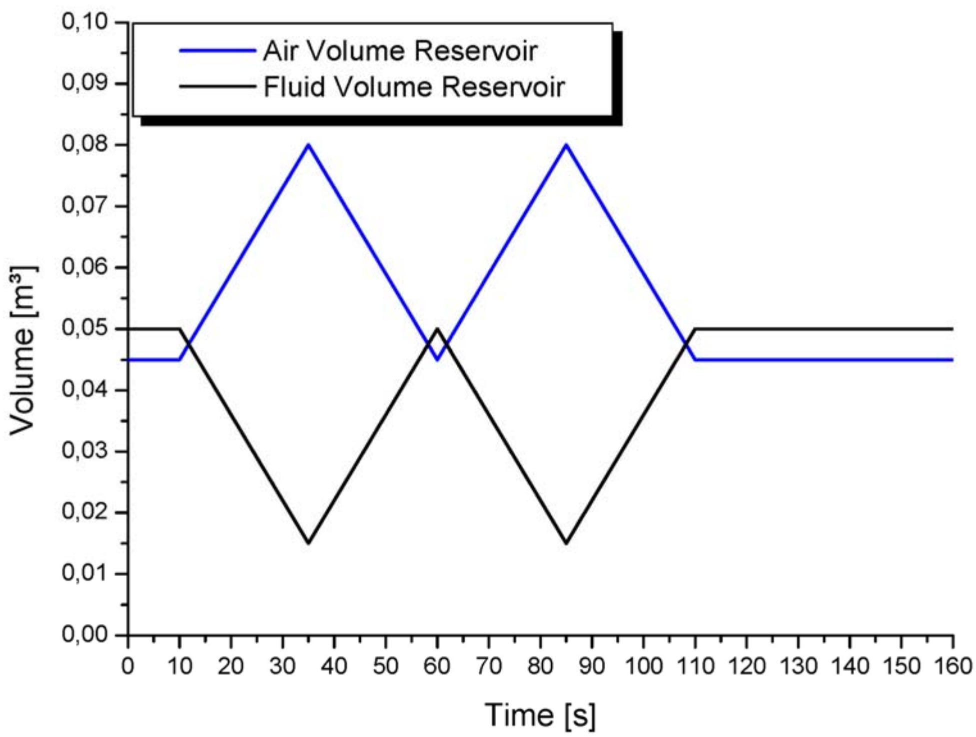
Ambient Conditions: $p = 1.013\ 10^5$ Pa $T = 288.15$ K = 15°C

Simulation Time: $\Delta t = 160$s

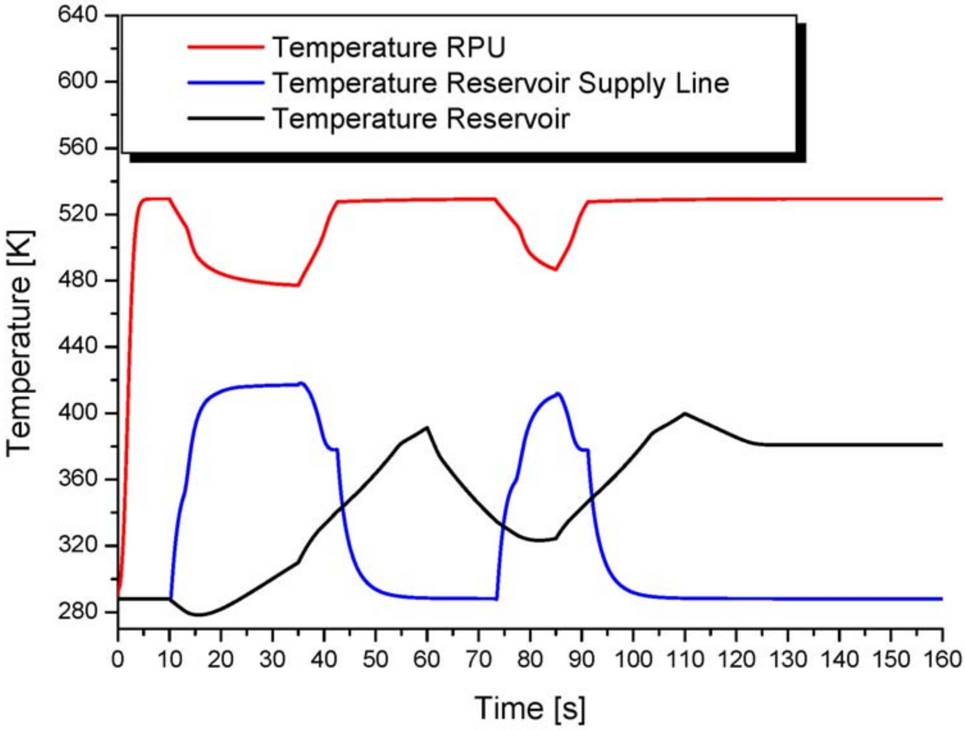
Time Step: $dt = 0.0001$s

Solver Type: ode4 (Runge-Kutta)

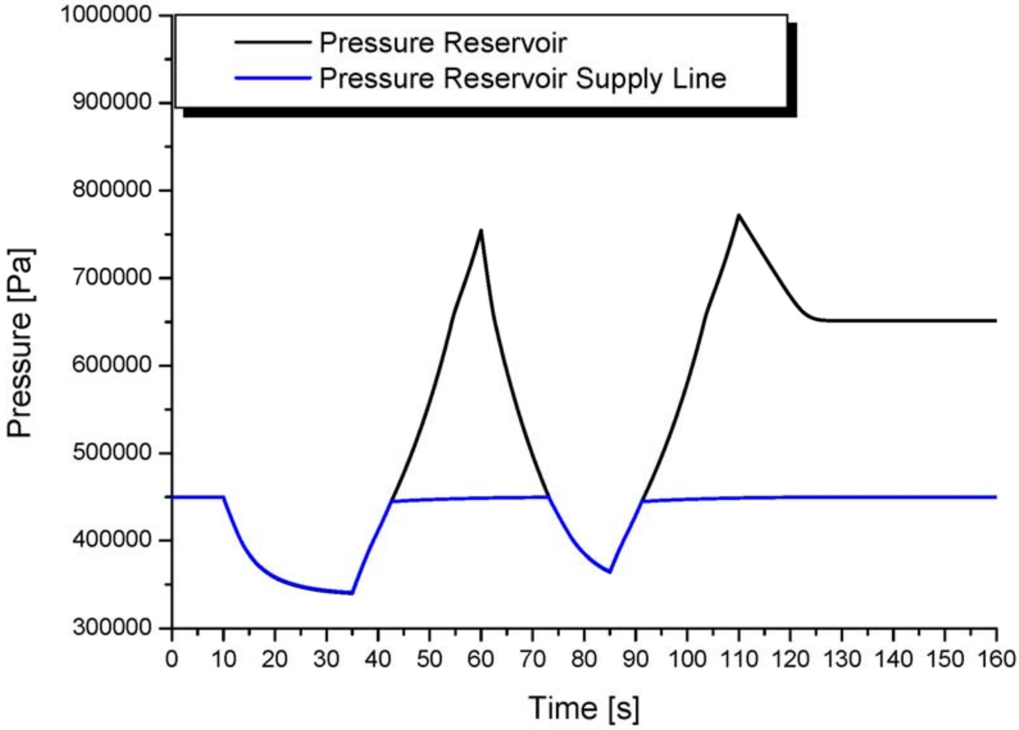
Hydraulic Fluid Level Variation:



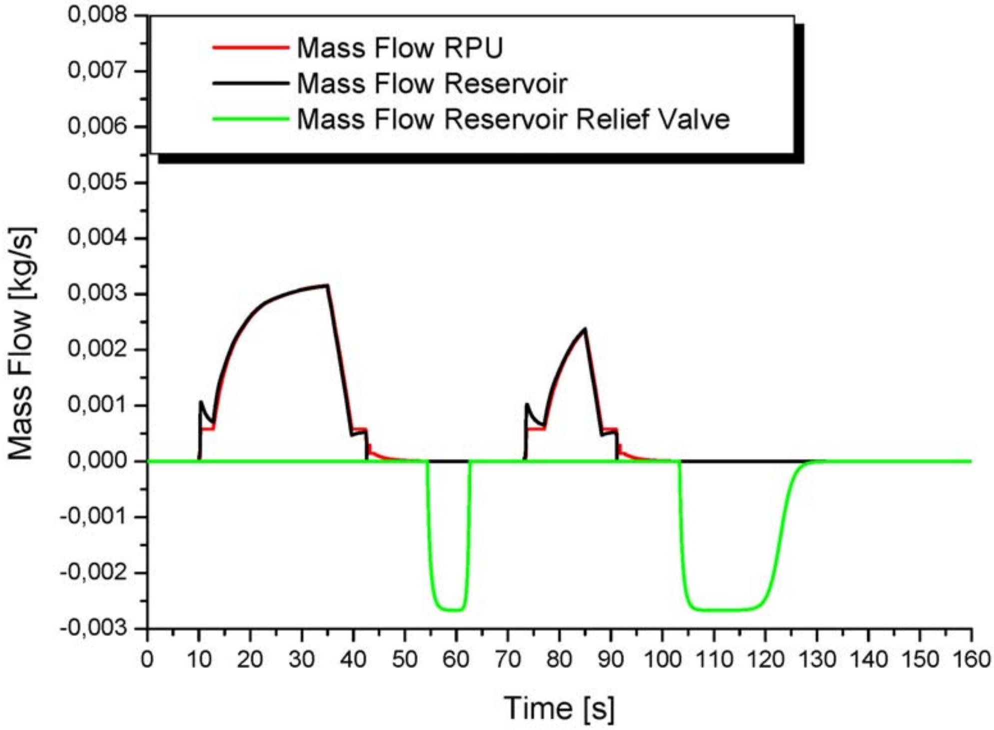
Temperature Profiles:



Pressure Distributions:



Mass Flow Distributions:



Density Reservoir: