

Vývoj digitálního dvojčete

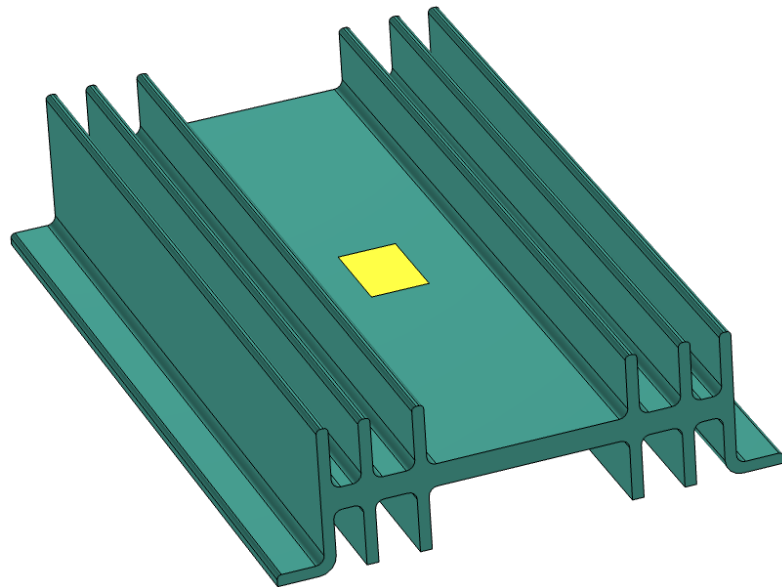
Ing. Aleš Hrouda, Ing. Matouš Lorenc

27.- 28. 5. 2021

Přehled

1. Vývoj výpočtového modelu
2. Přenesení MKP modelu do prostředí Simulink
3. Identifikace systému
4. Řízení výpočtového modelu

Vývoj výpočtového modelu



Equation

Equation form:

Show eq

Proudění a teplo

$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_{ted}$

Reference

T_{ref} User defined

293.15[K]

Isothermal domain

Discretization

Dependent Variables

Temperature: T



The screenshot shows a software interface for a fluid flow and heat transfer simulation. A blue box highlights the title "Proudění a teplo". The interface includes a 3D model of the heat exchanger core with a color scale for temperature, a reference temperature of 293.15[K], and a dependent variable "Temperature: T". The color scale ranges from 20 to 250, with a blue-to-red gradient. A small 3D model of a flame is also visible in the bottom right corner.



Model Builder

- Digital_twin.mph (root)
 - Global Definitions
 - Parameters 1
 - Default Model Inputs
 - Materials
 - Component 1 (comp 1)
 - Definitions
 - Selections
 - Boundary Point Probe 1
 - Point Probe Expression 1 (ppb 1)
 - Point Probe Expression 2 (ppb 2)
 - Point Probe Expression 3 (ppb 3)
 - Boundary Probe 1 (bnd 1)
 - Boundary System 1 (sys 1)
 - View 1
 - View 6
 - Geometry 1
 - Materials
 - Aluminum (mat 1)
 - Air (mat 2)
 - Heat Transfer in Solids (ht)
 - Laminar Flow (spf)
 - Multiphysics
 - Meshes
 - Convection+radiation
 - Convection without radiation
 - Results

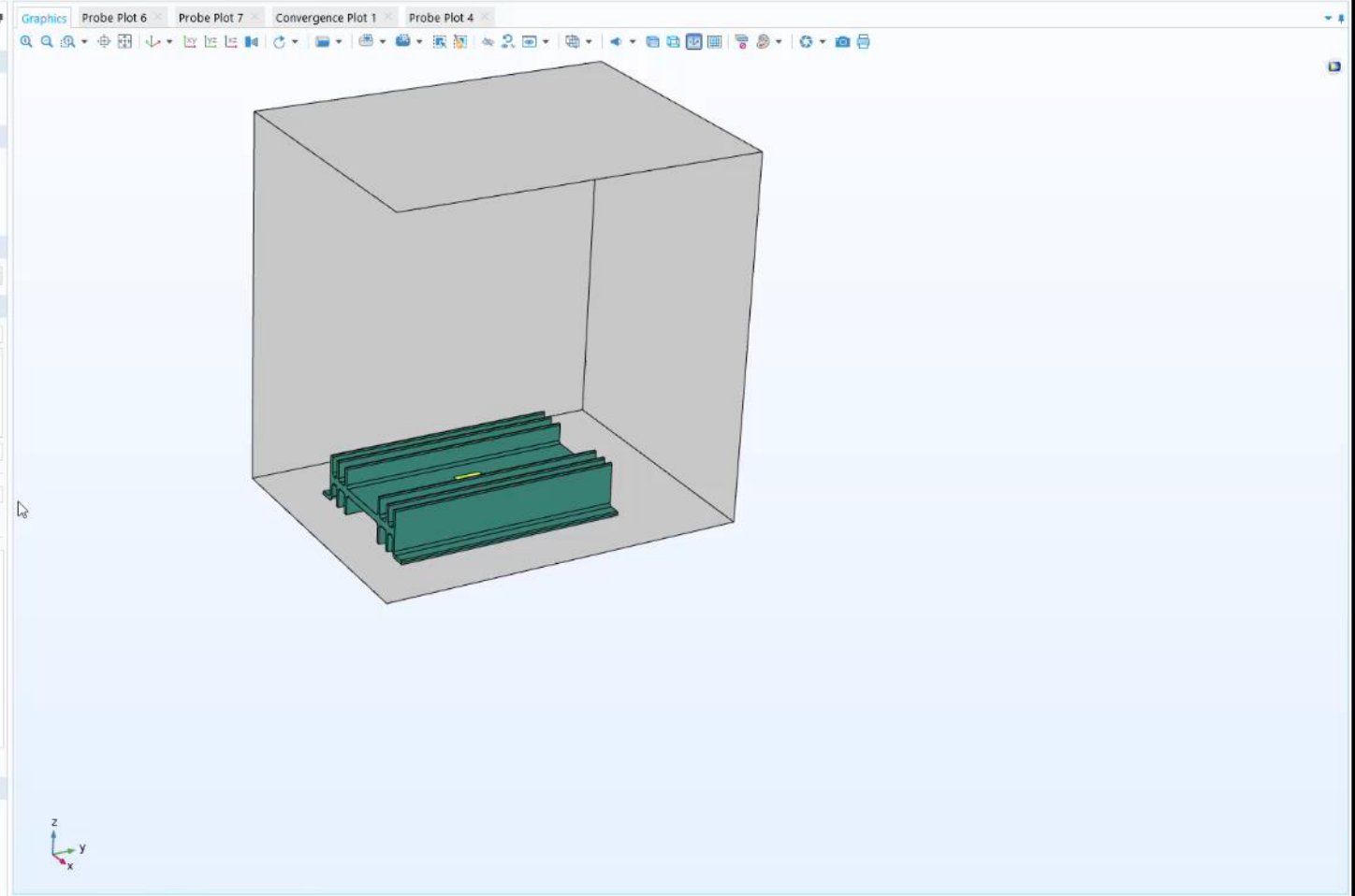
Settings

Digital_twin.mph

- Protection
 - Editing not protected
 - Running not protected
- Used Products
 - COMSOL Multiphysics
 - CAD Import Module
 - Design Module
 - Heat Transfer Module
- Unit System
 - SI
- Presentation
 - Title
 - Description
 - Author
 - Computation time
 - Expected
 - Last: 3 h 25 min 22 s
 - Thumbnail

Graphics

- Graphics color theme: Default from preferences (Default)
- Image export color theme: Default from preferences (Default)
- Font
- Family: Default from preferences (Vera)
- Size: Default size



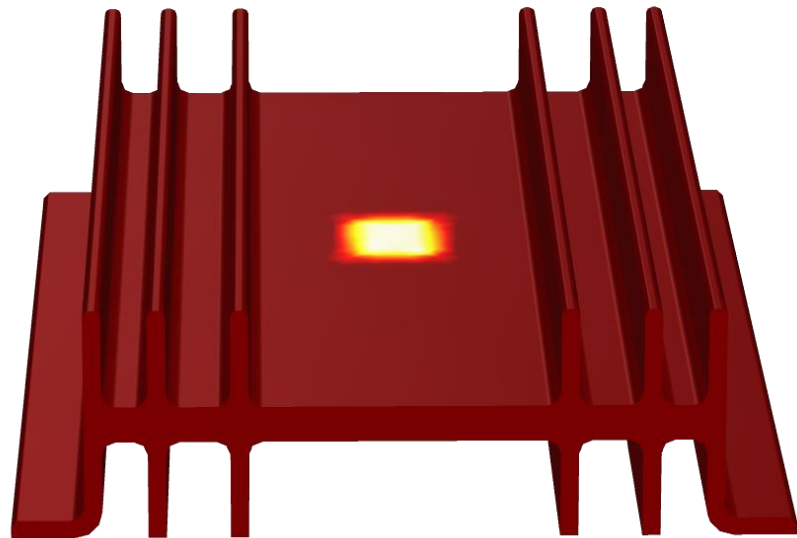
Messages

- Progress
- Log
- Probe Table 4

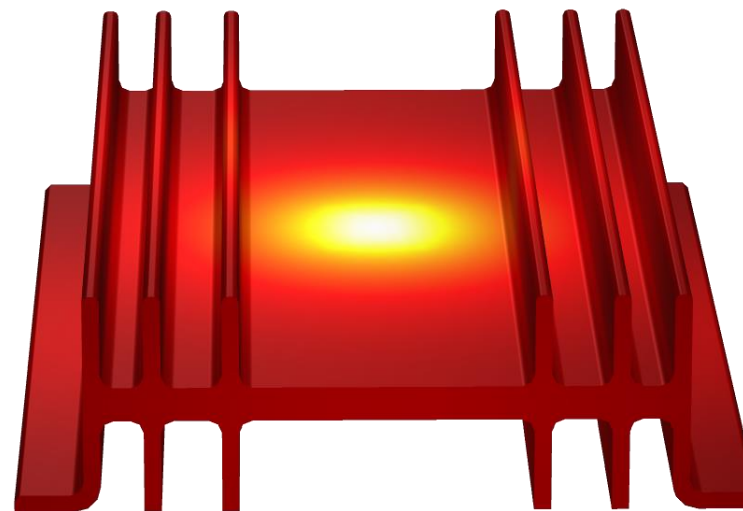
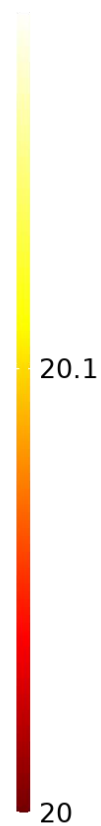
```

License will expire in 370 days.
Warning: The preference setting 'Number of cores is ignored because the environment variable 'OMP_NUM_THREADS' is set to '16'.
[May 24, 2021 4:13 PM] Opened file: D:\Digital_twin\Digital_twin.mph
[May 24, 2021 4:13 PM] Some geometric entities are hidden.
[May 24, 2021 4:14 PM] Complete mesh consists of 149487 domain elements, 20505 boundary elements, and 4124 edge elements.
[May 24, 2021 4:15 PM] Number of degrees of freedom solved for: 441331 (plus 361756 internal DOFs).
[May 24, 2021 7:40 PM] Solution time (Convection+radiation): 12322 s. (3 hours, 25 minutes, 22 seconds)
[May 25, 2021 10:08 AM] Saved file: D:\Digital_twin\Digital_twin.mph
[May 25, 2021 10:51 AM] Formed union of 2 solid objects and 1 surface object.
[May 25, 2021 10:51 AM] Union has 2 domains, 138 boundaries, 342 edges, and 208 vertices.
[May 25, 2021 10:51 AM] Finalized geometry has 2 domains, 95 boundaries, 274 edges, and 184 vertices.
[May 25, 2021 10:52 AM] Complete mesh consists of 149487 domain elements, 20505 boundary elements, and 4124 edge elements.
  
```

Výsledek rozložení teploty



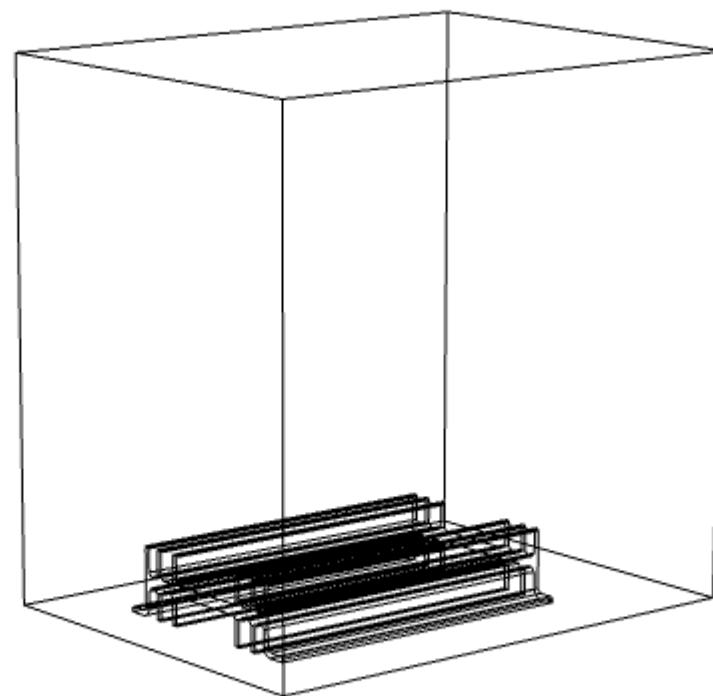
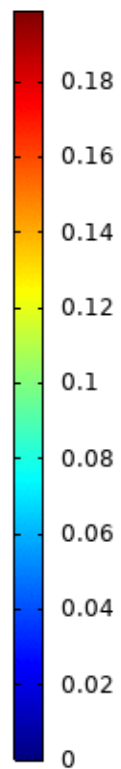
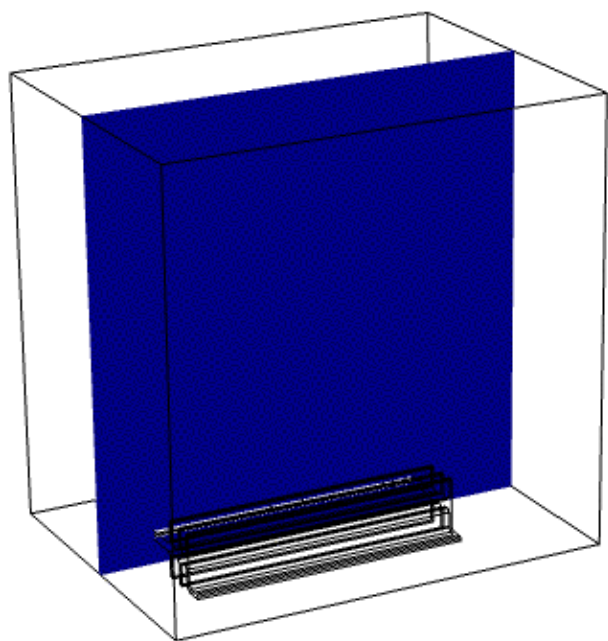
t=0 s



t = 900 s



Time=0 s

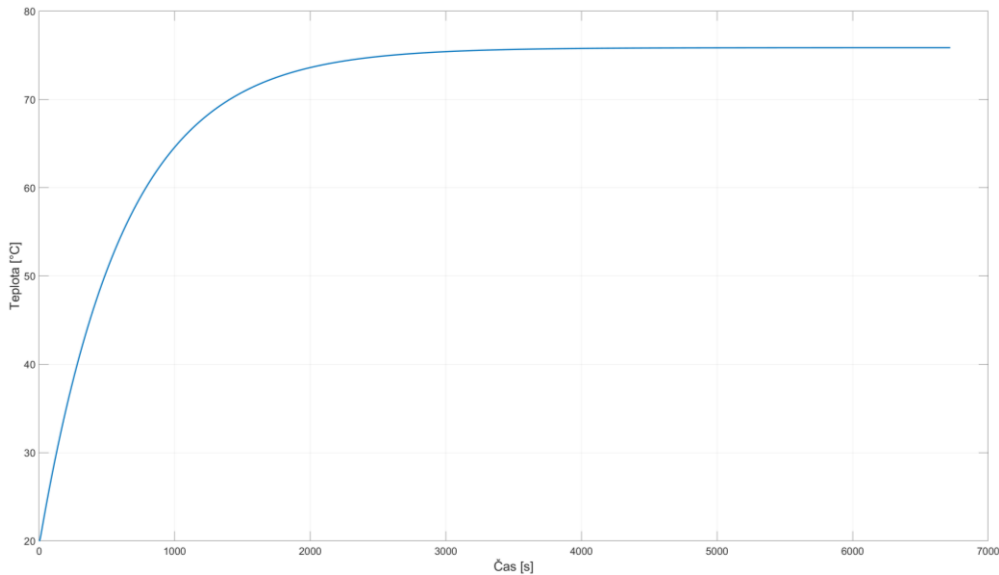


Rychlost [m/s]

Teplota [°C]

Pouze teplotní úloha

- Parameter estimation



Input – výsledek z úlohy s laminárním prouděním

Heat Flux

General inward heat flux

Convective heat flux

$q_0 = h \cdot (T_{\text{ext}} - T_2)$

Heat transfer coefficient:

User defined

Heat transfer coefficient:

h htc W/(m²·K)

External temperature:

T_{ext} User defined 293.15[K] K

Heat rate

$q_0 = \frac{P_0}{A}$

Study 2

Parameter Estimation

Step 1: Time Dependent

Solver Configurations

Reference Data

Reference data source: Interpolation function

Reference function: Interpolation 10 (int10)

Parameters

Parameter name	Initial value	Scale	Lower bound	Upper bound
htc	44	1	1	70

Algoritmy:

- **BOBYQA**

Použití na estimaci geometrie/sítě

- **Levenberg- Marquardt**

Nepodporuje podmínky

- **SNOPT**

Podporuje okrajové podmínky

Model Builder

- New.mph (root)
 - Global Definitions
 - Parameters 1
 - Default Model Inputs
 - Materials
 - Reduced-Order Modeling
 - Cosimulation for Simulink 1
 - Component 1 (comp 1)
 - Definitions
 - Geometry 1
 - Materials
 - Heat Transfer in Solids 2 (ht2)
 - Mesh 2
 - Study 1
 - Study 4
 - Study 3
 - Model Reduction
 - Step 1: Time Dependent
 - Solver Configurations
 - Job Configurations
 - Study 5
 - Results

Settings

Cosimulation for Simulink

Export

Label: Cosimulation for Simulink 1

Filename: D:\Digital_twin\Reduced_order3.fmu Browse...

Inputs

Parameter name	Initial value	Unit
P0	16[W]	W

Block Parameters

Outputs

Expression	Unit	Name
comp1.ppb2	K	Boundary Point Probe 2, T2

Expression:

Name:

Study

Study: Study 5

Store solution:

At communication points: End of communication step

According to study step settings

Dependencies

Parameter name	Initial value	Unit	Dependencies
P0	16[W]	W	comp1.ppb2

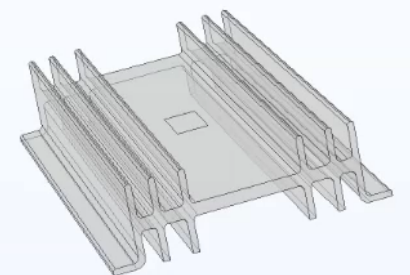
Image

Image:

Browse... Import Set from Graphics Window

Image preview

Graphics



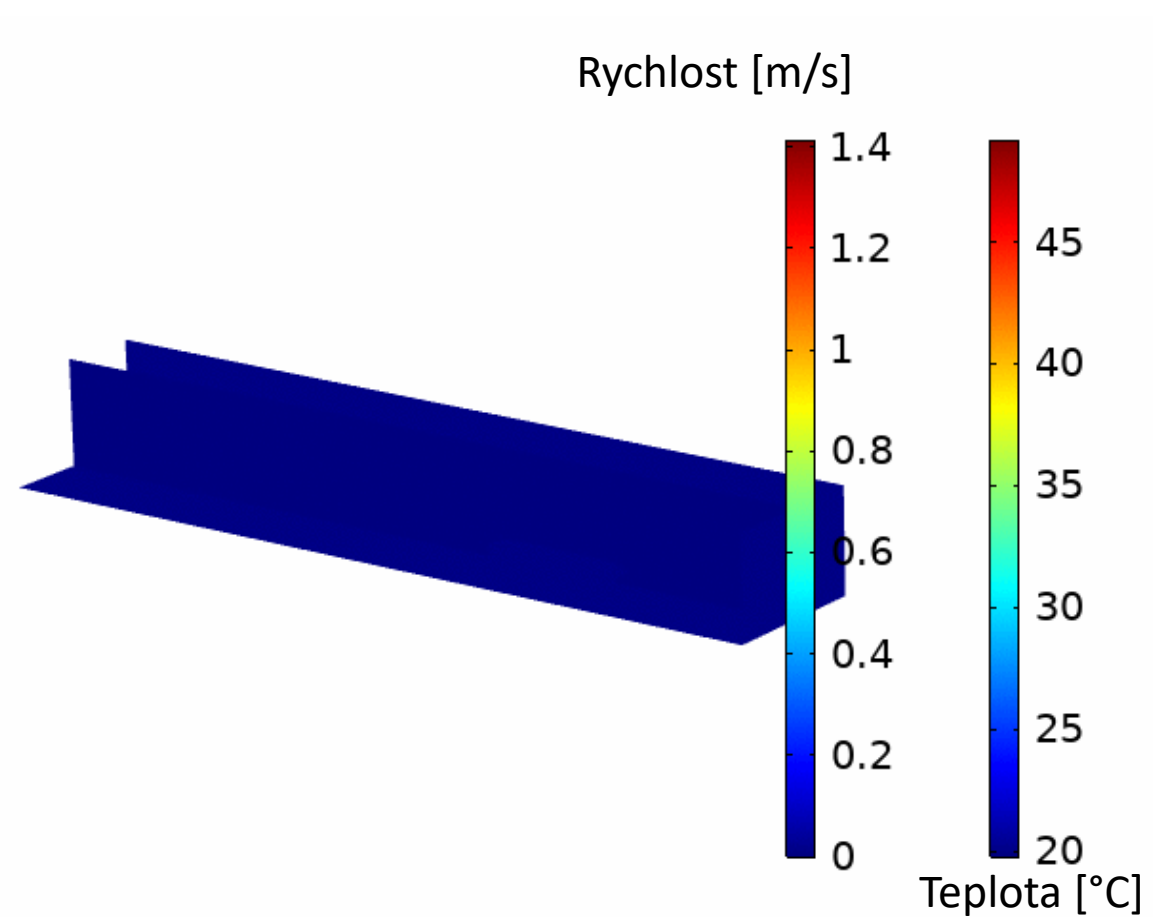
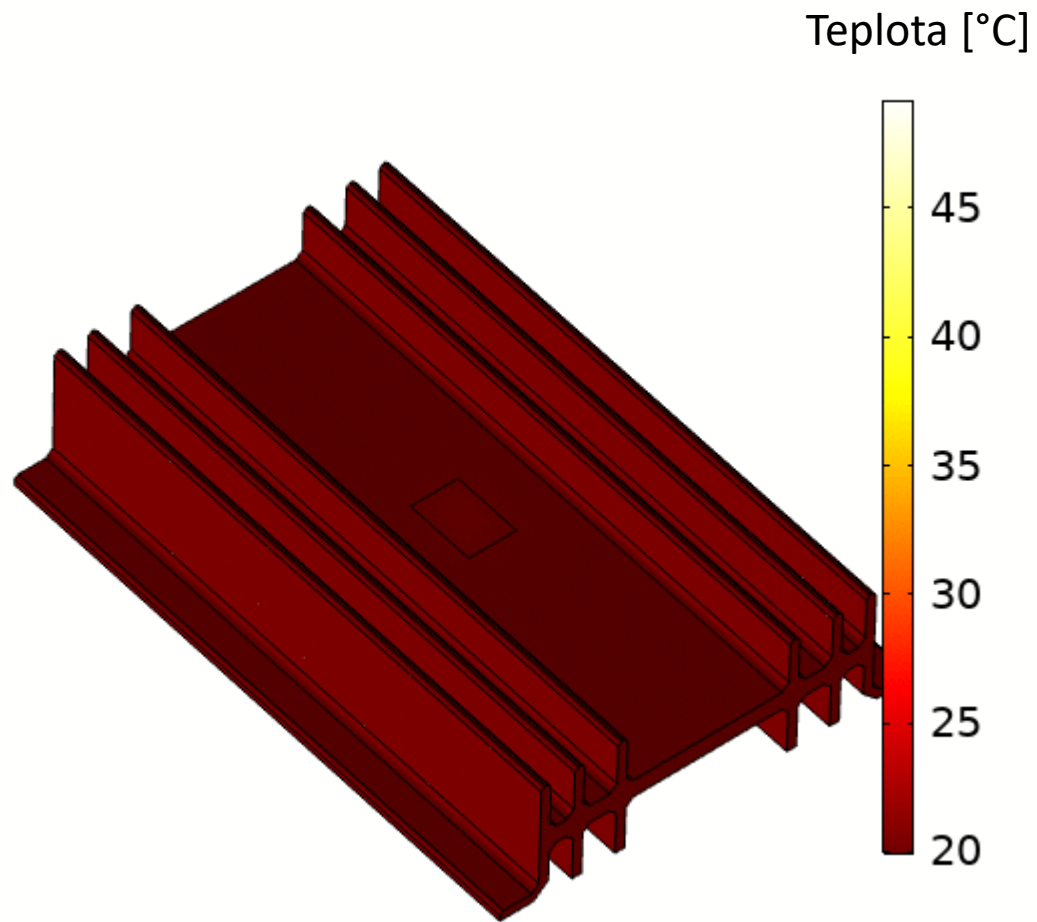
Messages | Progress | Log | Probe Table 1

COMSOL Multiphysics 5.6.0.280
License will expire in 36 days.

Warning: The preference setting Number of cores is ignored because the environment variable 'OMP_NUM_THREADS' is set to '16'.

[May 25, 2021 9:56 AM] Opened file: D:\Digital_twin\New.mph
 [May 25, 2021 9:56 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu
 [May 25, 2021 10:21 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu
 [May 25, 2021 10:23 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu
 [May 25, 2021 11:12 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu

Simulace s prouděním



Redukce systému

Redukovaný model

Redukce systému na základě vlastních čísel

- ▶ Nonreduced
- ▶ Eigenvalues
- ▶ Reduced

Model Reduction Settings

Method: Modal

Training study: Eigenvalues

Defined by study step: Automatic

Compute: Always

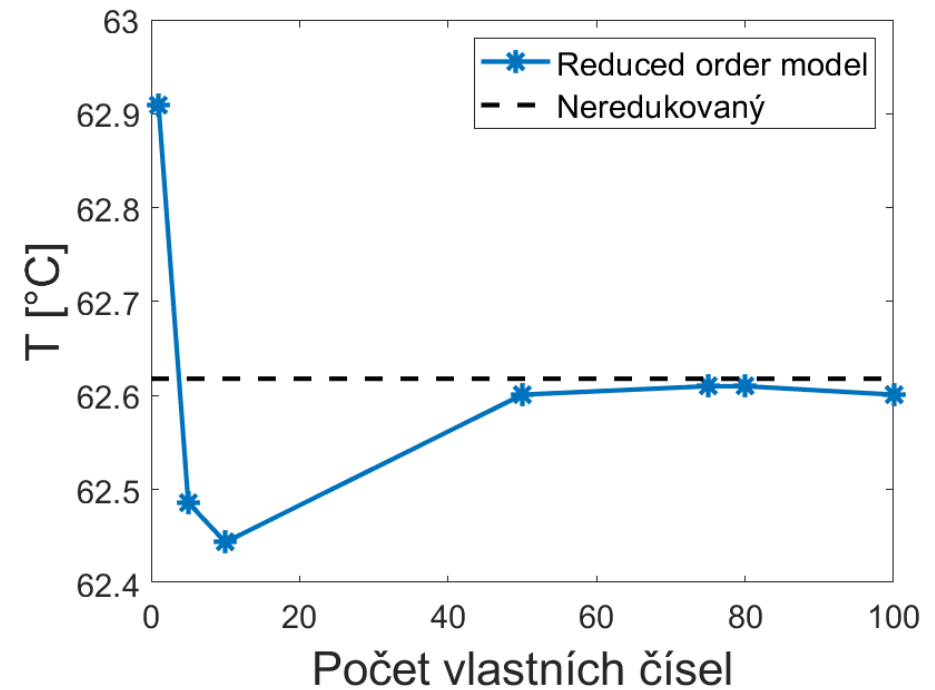
Unreduced model study: Nonreduced

Defined by study step: Time Dependent

Reduced-order model: Time Dependent, Modal Reduced-Order Model 1 (rom1)

Ensure reconstruction capability

Store reduced matrices



COMSOL Multiphysics 5.6.0.280

Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Component Add Component Parameters Variables Functions Import Level Link Add Material Heat Transfer in Solids Add Physics Build Mesh Compute Study Add Study 1D Plot Add Plot Group Group Windows Reset Desktop

Model Builder

- New.mph (root)
 - Global Definitions
 - Parameters 1
 - Default Model Inputs
 - Materials
 - Reduced-Order Modeling
 - Global Reduced Model Inputs 1
 - Time Dependent, Model Reduced-Order Model 1 (rsm?)
 - Cosimulation for Simulink 1
 - Component 1 (comp?)
 - Definitions
 - Geometry 1
 - Materials
 - Heat Transfer in Solids 2 (ht2)
 - Mesh 2
 - Study 1
 - Study 4
 - Study 3
 - Model Reduction
 - Step 1: Time Dependent
 - Solver Configurations
 - Job Configurations
 - Study 5
 - Results

Settings

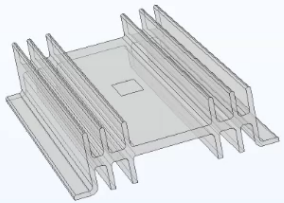
Global Reduced Model Inputs

Label: Global Reduced Model Inputs 1

Reduced Model Inputs

Control name	Expression
P0	16[W]

Graphics



Messages | Progress | Log | Probe Table 1

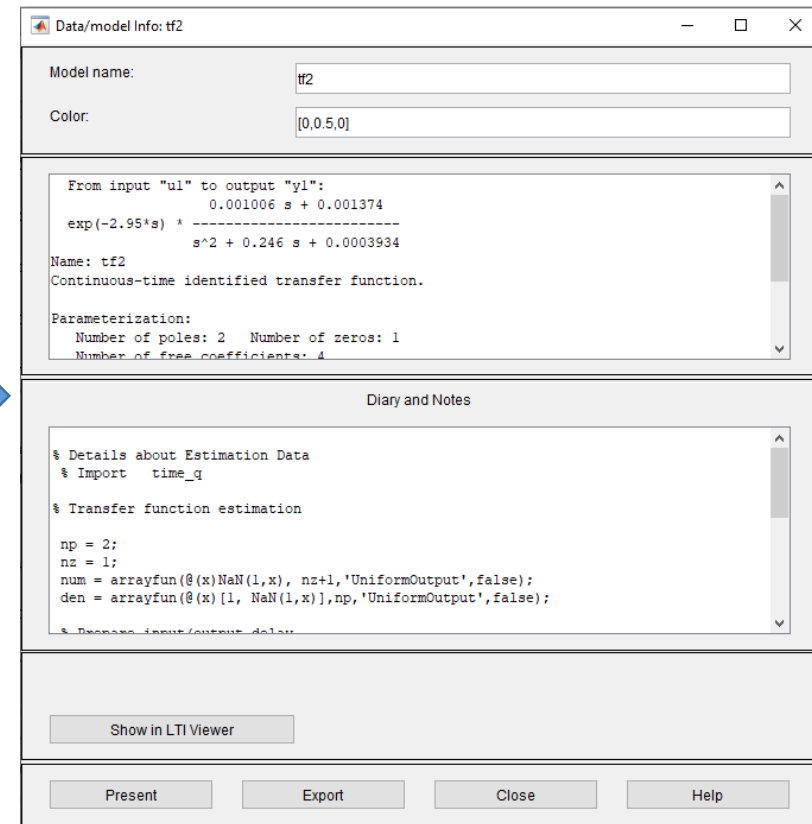
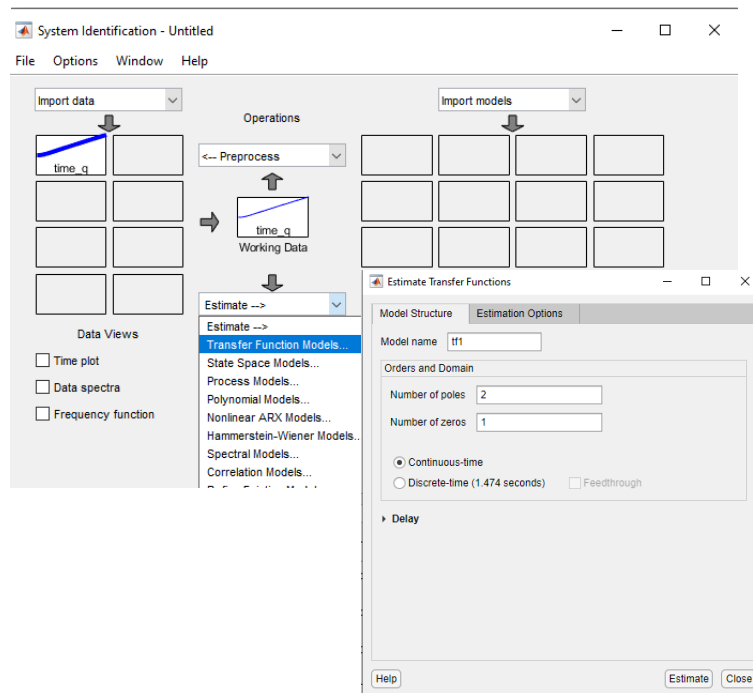
COMSOL Multiphysics 5.6.0.280
License will expire in 36 days.
Warning: The preference setting Number of cores is ignored because the environment variable 'OMP_NUM_THREADS' is set to '16'.
[May 25, 2021 9:56 AM] Opened file D:\Digital_twin\New.mph
[May 25, 2021 9:56 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu
[May 25, 2021 10:21 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu
[May 25, 2021 10:23 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu
[May 25, 2021 11:12 AM] Saved file for cosimulation for Simulink: D:\Digital_twin\Reduced_order3.fmu

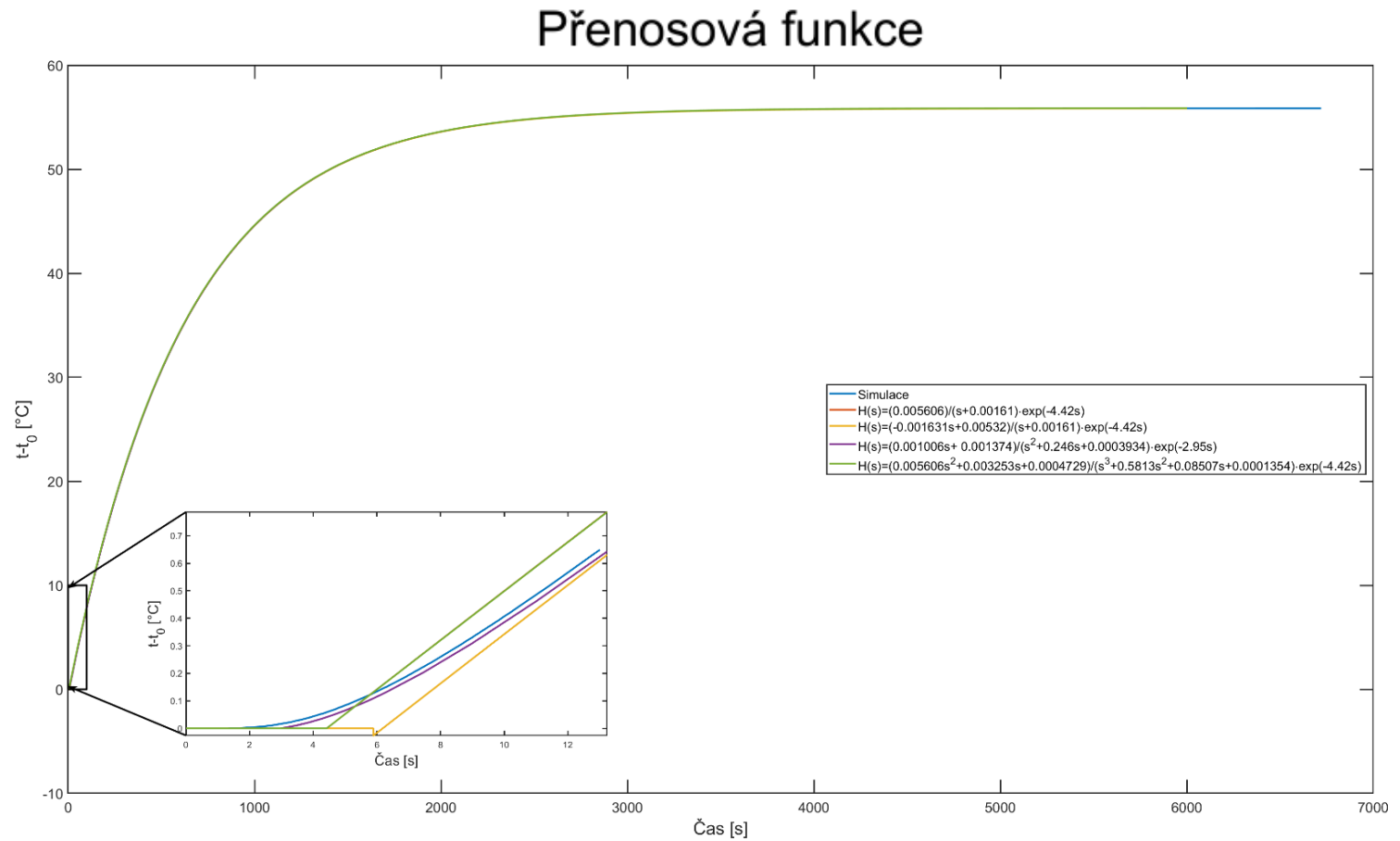
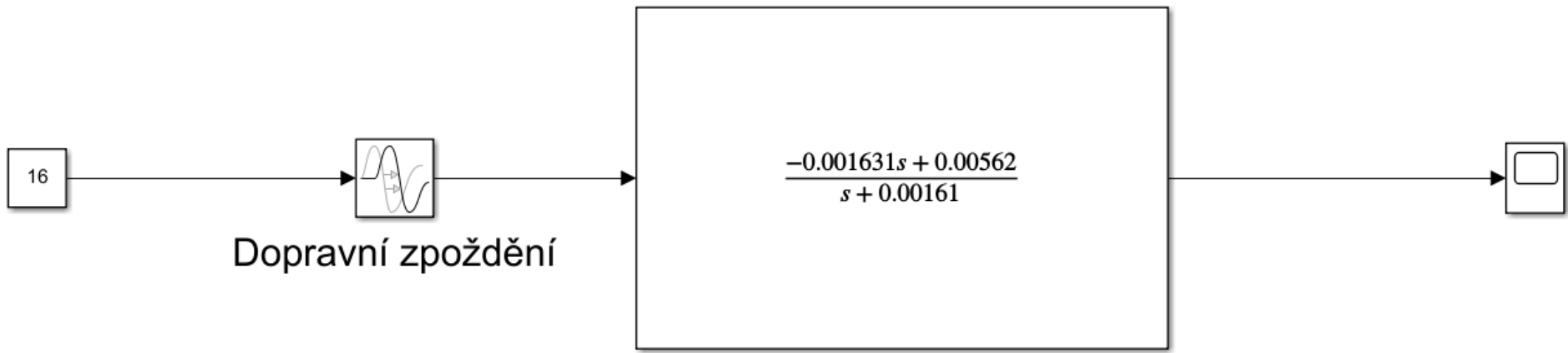
1.75 GB | 2.04 GB

Řízení systému

Identifikace systému

- Nalezení přenosové funkce
- Toolbox Systém Identification





Import matic z Comsolu do Matlabu

- Při uložení matic ve workspace lze spouštět i Simulink

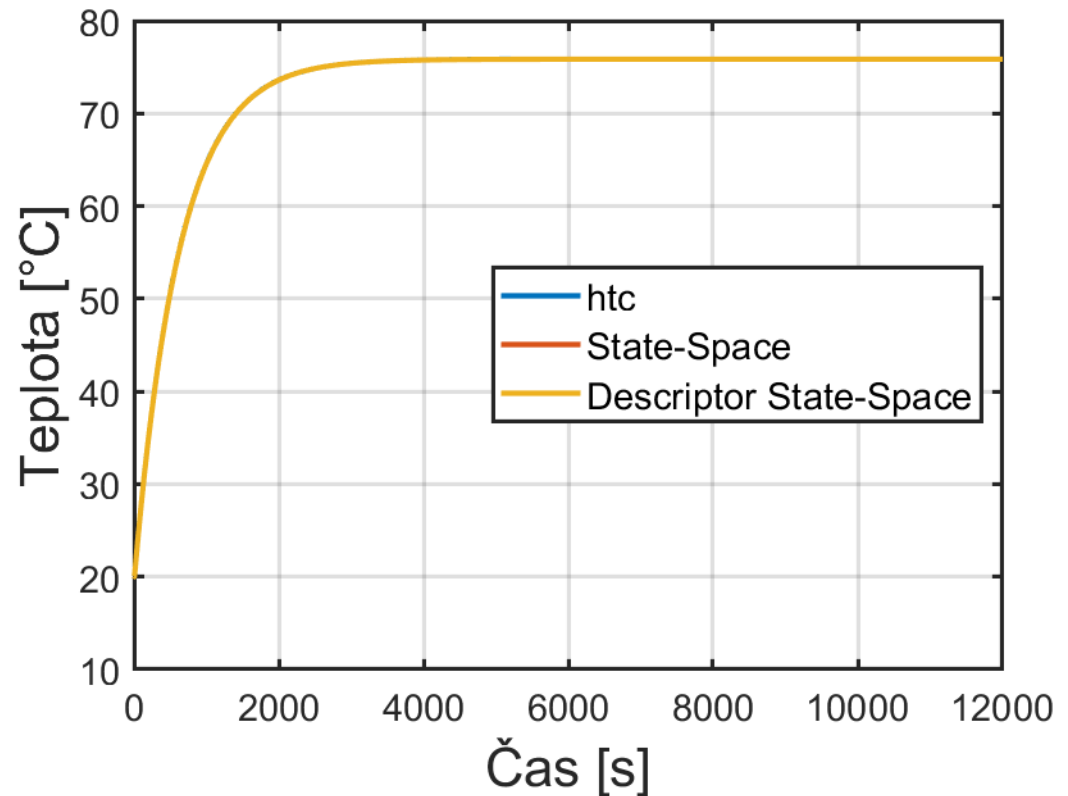
```
model=mphload("New.mph"); %Nacteni souboru
MR=mphreduction(model, 'roml','out',{ 'Mc' 'MA' 'MB' 'A' 'B' 'C' 'D' 'x0'});
% vytahnuti matic ze systemu
input=16;% vstup
func=@(t,x) MR.MA*x+MR.MB*input';% vypoctova rovnice
opt=odeset('mass',MR.Mc, 'Jacobian',MR.MA, 'stats','on');
x0=zeros(size(MR.MA,1),1);
[t,x2]=ode23s(func,0:0.05:900,x0,opt);
y2t=MR.C*x2';
y20=MR.C*MR.x0;
y2=y2t+y20;
```

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$

State-space

$$\begin{cases} E\dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$

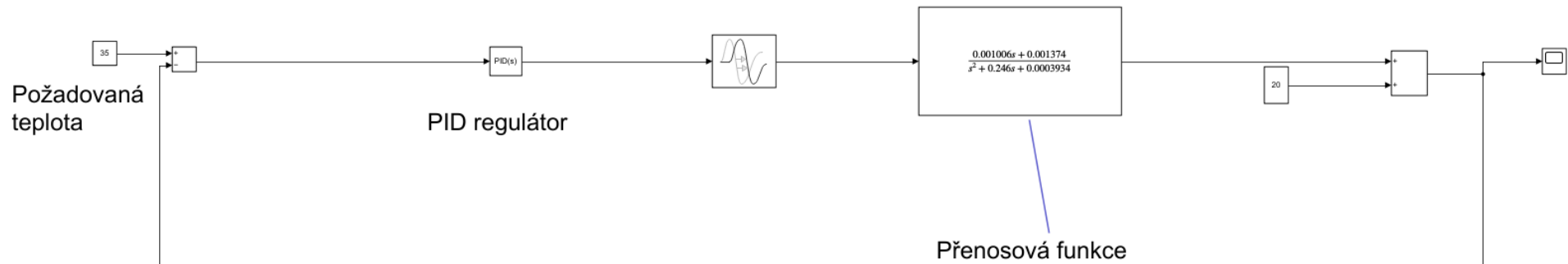
Descriptor State-Space



Matrices	
Stiffness matrix (Kr)	
Damping matrix (Dr)	
Damping ratio matrix (Dra)	
Mass matrix (Er)	
Input matrix (Br)	
Output matrix (Cr)	
Input feedback matrix (F)	
Initial value input matrix (B0r)	
Initial value time derivative input matrix (B0rdot)	
Time derivative input matrix (Brdot)	
Second time derivative input matrix (Brdotdot)	
Mass matrix (Mc)	
Stiffness matrix (MA)	
Input matrix (MB)	
Input feedback matrix (D)	
Output matrix (C)	
Vectors	
Load vector (L)	
Output bias (Y0)	
Initial value vector (U0)	
Initial derivative vector (Udot0)	
Stiffness matrix times ud (Kud)	
Initial value vector (x0)	

Kontrola řízení pomocí PID regulátoru

PID controller tuning



Block Parameters: PID Controller1

PID 1dof (mask) (link)

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PID Form: Parallel

Time domain:
 Continuous-time
 Discrete-time

Discrete-time settings
Sample time (-1 for inherited): -1

Compensator formula
$$P + I \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}}$$

Main Initialization Output Saturation Data Types State Attributes

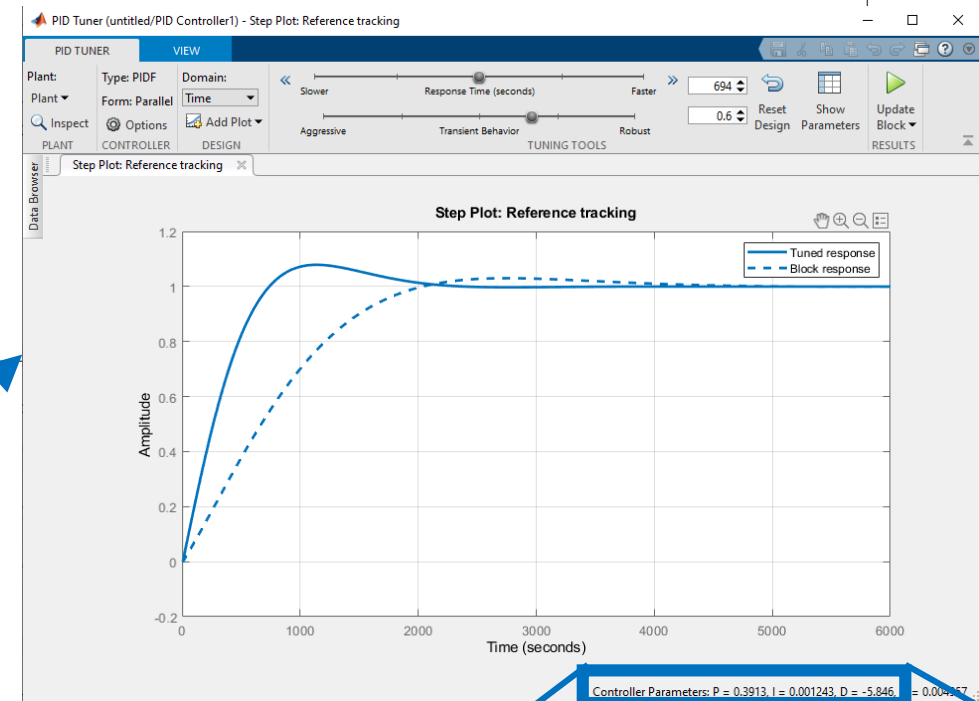
Controller parameters
Source: internal

Proportional (P): 0.39129858652236
Integral (I): 0.00124338056559832
Derivative (D): -5.84633686673602
 Use filtered derivative
Filter coefficient (N): 0.00495721058288111

Automated tuning
Select tuning method: Transfer Function Based (PID Tuner App) **Tune...**

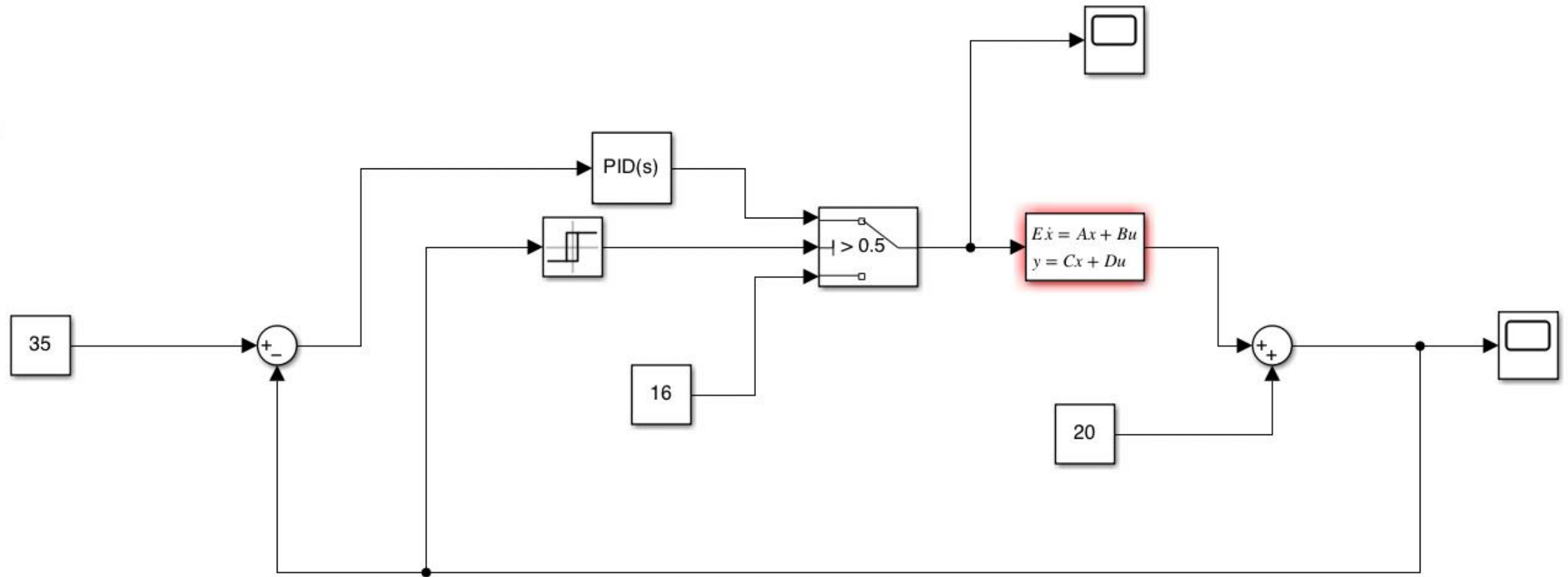
Enable zero-crossing detection

OK Cancel Help Apply

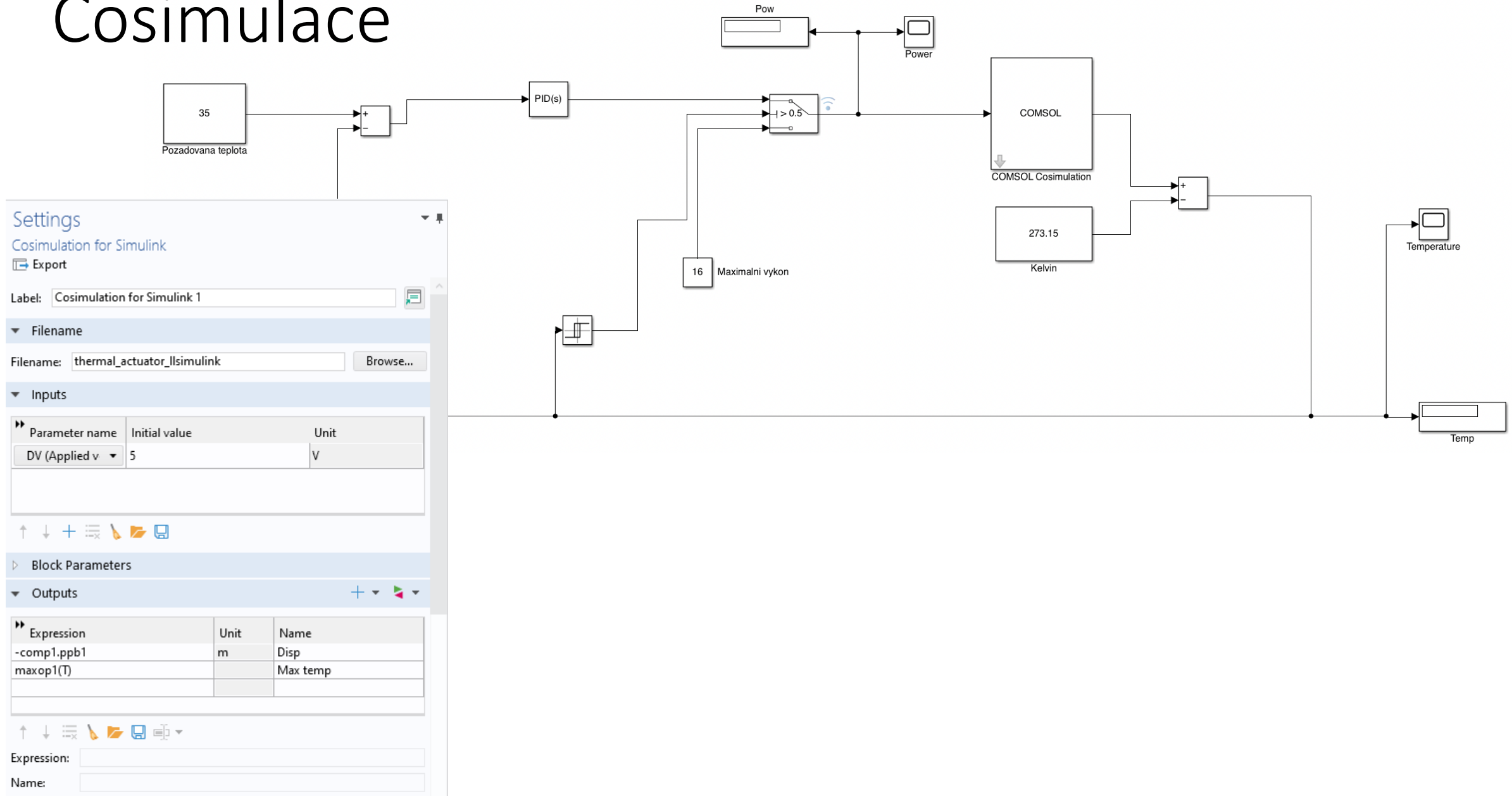


P=0.3913, I= 0.001243, D = -5.846

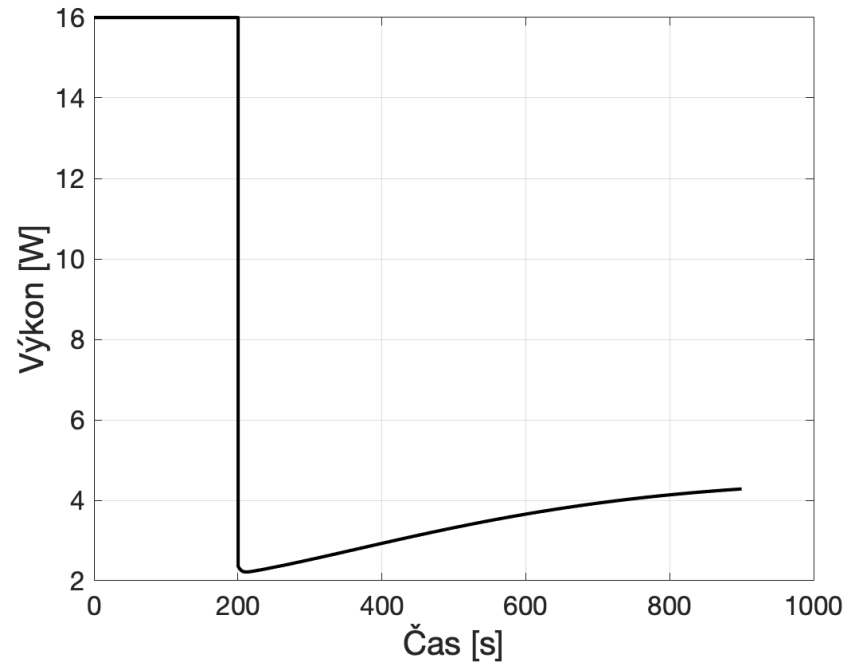
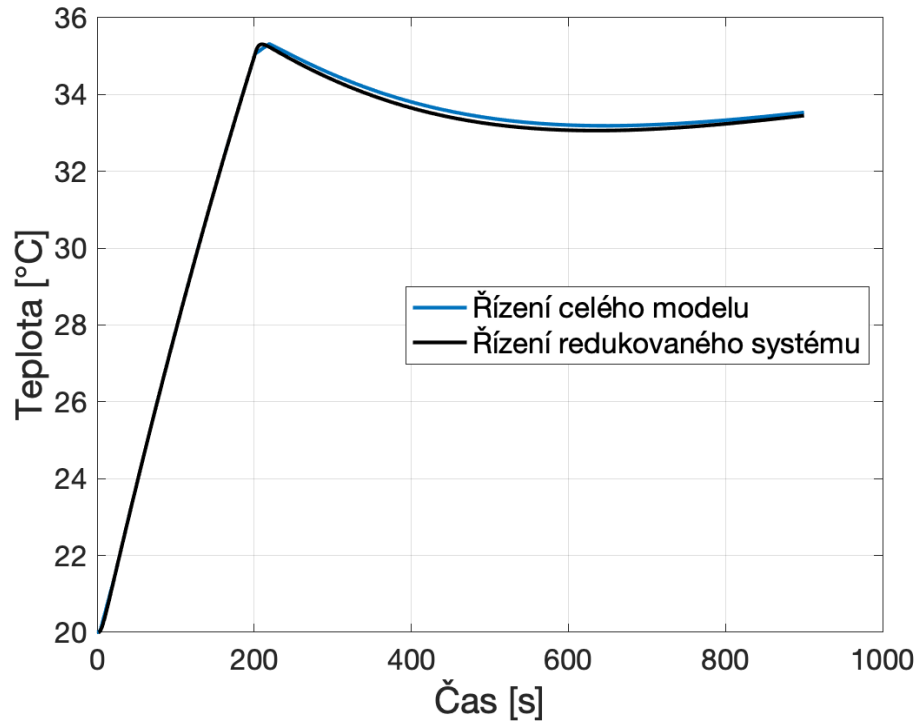
Vložení matic z redukovaného systému



Cosimulace



Co-simulace



Metoda	Čas
Co-simulace	15 min 19 sec
Import matic	2 sec

Poznámka v případě problému komunikace do Command Window: [shareMATLABForFMUCoSim](#)

Děkuji za pozornost