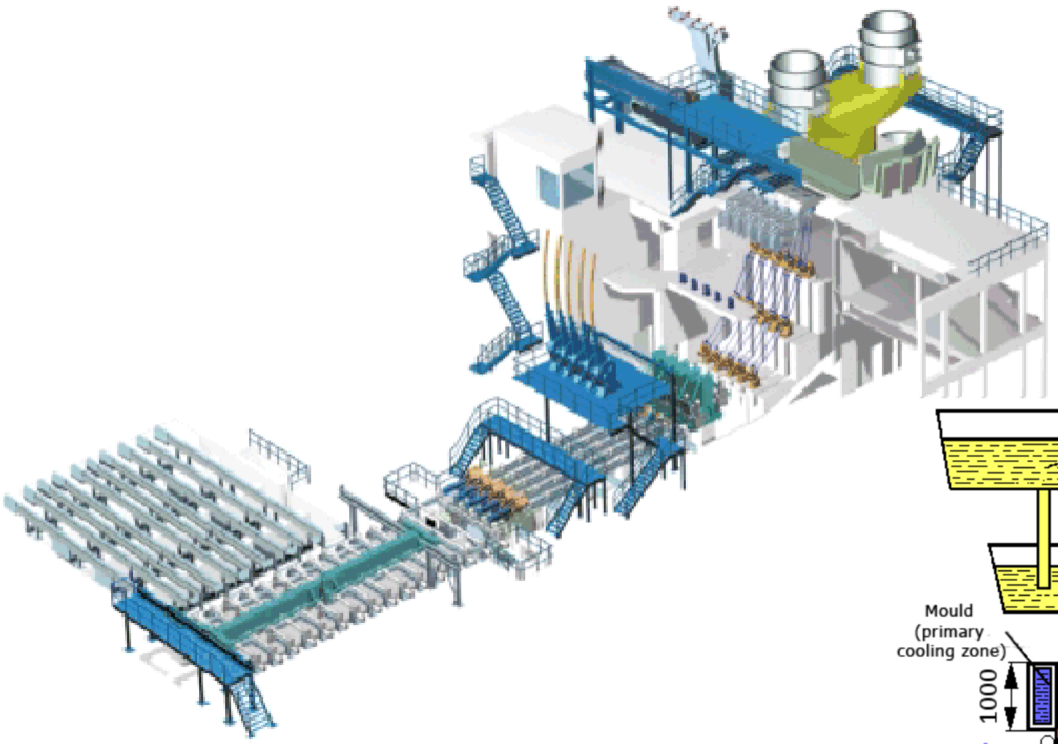
BRNO UNIVERSITY OF TECHNOLOGY
FACULTY MECHANICAL ENGINEERING – ENERGY INSTITUTE

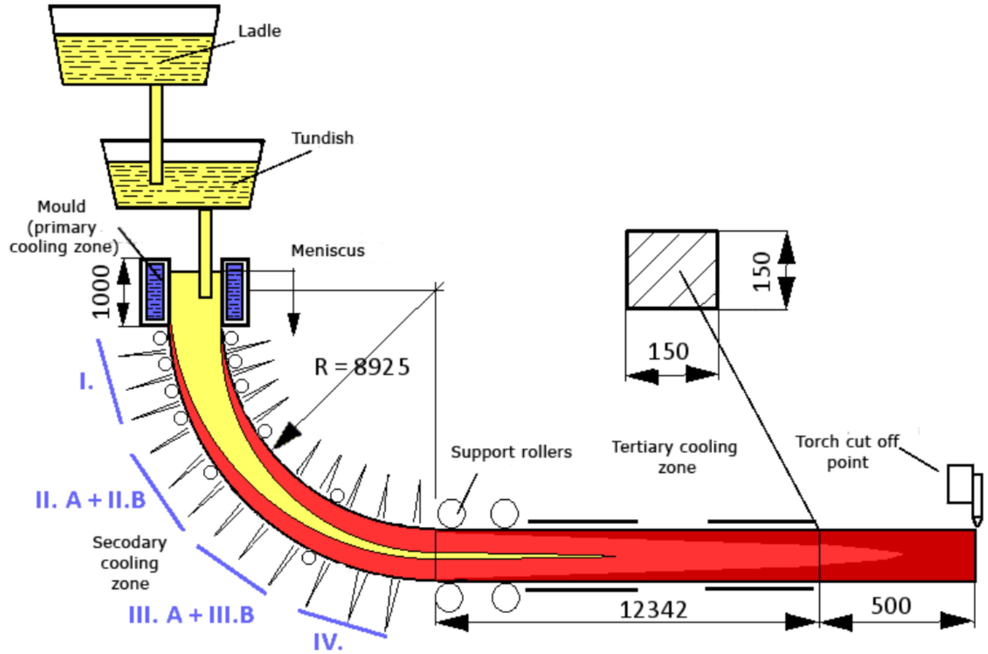
NOVÉ MOŽNOSTI ŘÍZENÍ PLYNULÉHO ODLÉVÁNÍ OCELI NA ZÁKLADĚ DYNAMICKÉHO MODELU TUHNUTÍ

Josef ŠTĚTINA
Lubomír KLIMEŠ

http://www.energetickeforum.cz/fsi-vut-v-brne/simulace-prumyslovych-procesu/

RADIAL BILLET CASTER





FOURIER-KIRCHHOFF'S EQUATION

$$\frac{\partial T}{\partial \tau} = \frac{k}{\rho \cdot c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \left(w_x \frac{\partial T}{\partial x} + w_y \frac{\partial T}{\partial y} + w_z \frac{\partial T}{\partial z}\right) + \frac{Q_{SOURCE}}{\rho \cdot c}$$

T	temperature	[K]
τ	time	[s]
k	heat conductivity	$[W.\ m^{-1}.K^{-1}]$
w	velocity	$[m\ s^{-1}]$
ρ	density	$[kg\ m^{-3}]$
c	specific heat capacity	$[J\ kg^{-1}K^{-1}]$
x,y,z	coordinates	[m]
Q_{SOURCE}	heat flow from internal source	$[W\ m^{-3}]$

IF

$$\left(w_y \frac{\partial T}{\partial y} + w_z \frac{\partial T}{\partial z}\right) = 0$$

THEN

$$\frac{\partial T}{\partial \tau} = \frac{k}{\rho \cdot c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \left(w_z \frac{\partial T}{\partial z}\right) + \frac{Q_{SOURCE}}{\rho \cdot c}$$

Boundary conditions:

1st $$T = T_{pour}$$

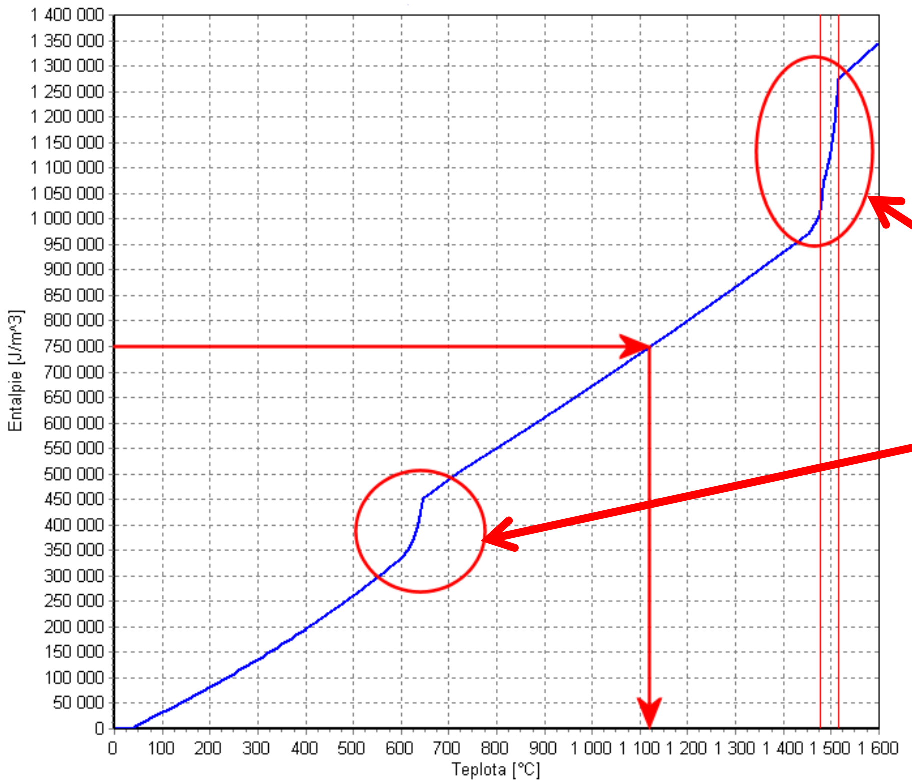
2nd $$-k\frac{\partial T}{\partial n} = 0$$

3rd $$-k\frac{\partial T}{\partial n} = HTC\,(T_{surf} - T_{mould})$$

4th $$-k\frac{\partial T}{\partial n} = HTC\,(T_{surf} - T_{amb}) + \sigma\varepsilon\left(T_{surf}^4 - T_{amb}^4\right)$$

ENTHALPY AS A FUNCTION OF TEMPERATURE

$$\rho\frac{\partial H}{\partial t}+\frac{\partial}{\partial z}\left(\rho .v_z .H\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)$$



$\rho(t)$ [kg.m^{-3}]

$k(t)$ [W.m^{-1}.K^{-1}]

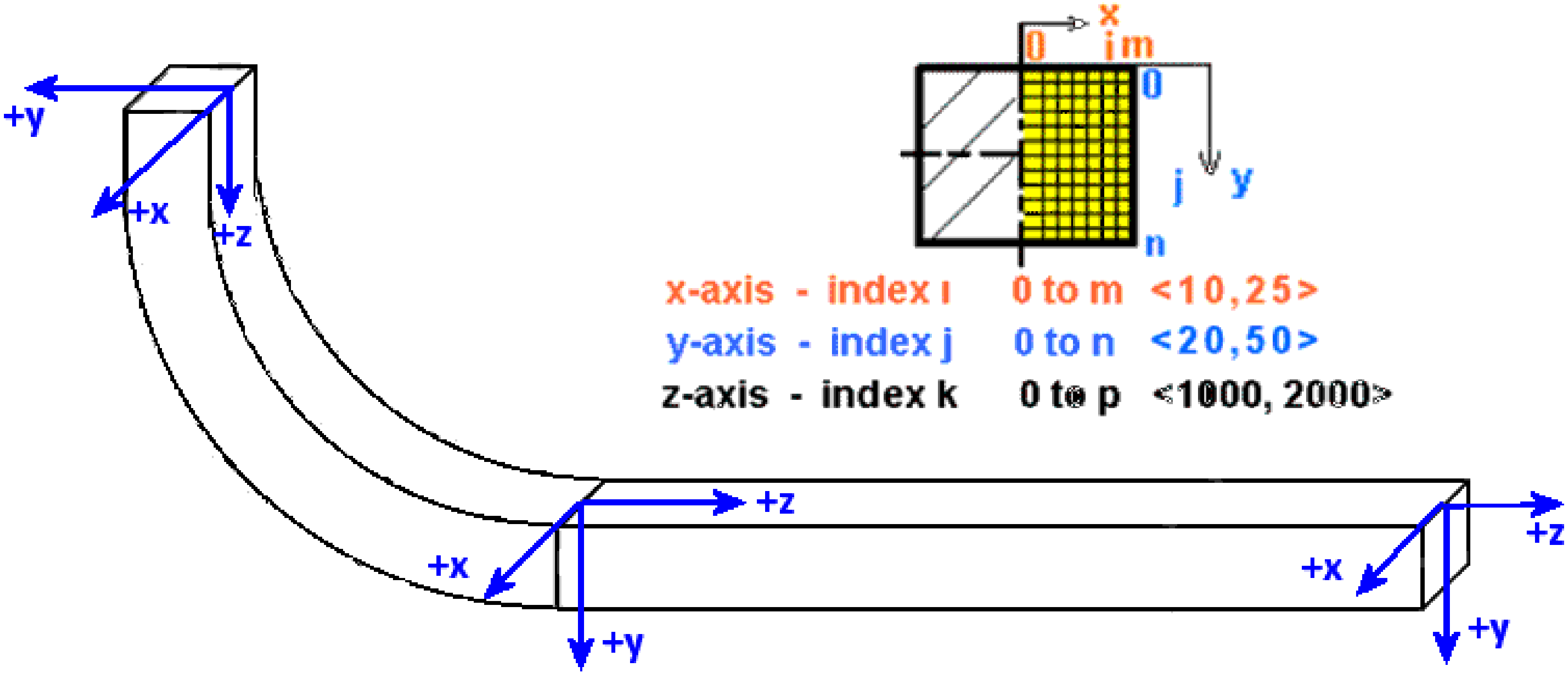
$c(t)$ [J.kg^{-1}.K^{-1}]

L [J]

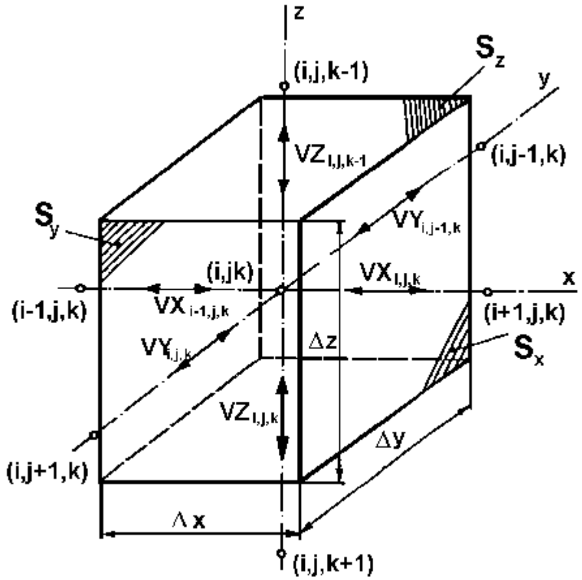
This point can change its phase or structure during the simulated process. The enthalpy function contains the latent or structural heat of each change.

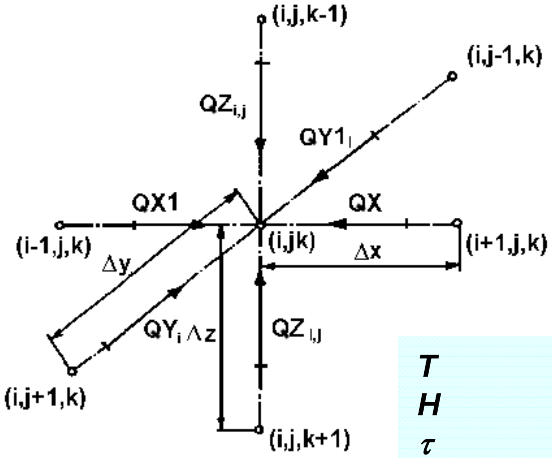
This function must be known for the relevant steel.

COMPUTING NETWORK



3D TEMPERATURE – FIELD ELEMENT





T	temperature	[K]
H	specific volume enthalpy	[W.m^{-3}]
τ	time	[s]
c_v	specific volume heat capacity	[J.m^{-3}.K^{-1}]
ρ	density	[kg m^{-3}]
x,y,z	axis in given direction	
QX,QY,QZ	heat flow in given direction	[W]
VX,VY,VZ	conductivity in given direction	[W.K^{-1}]

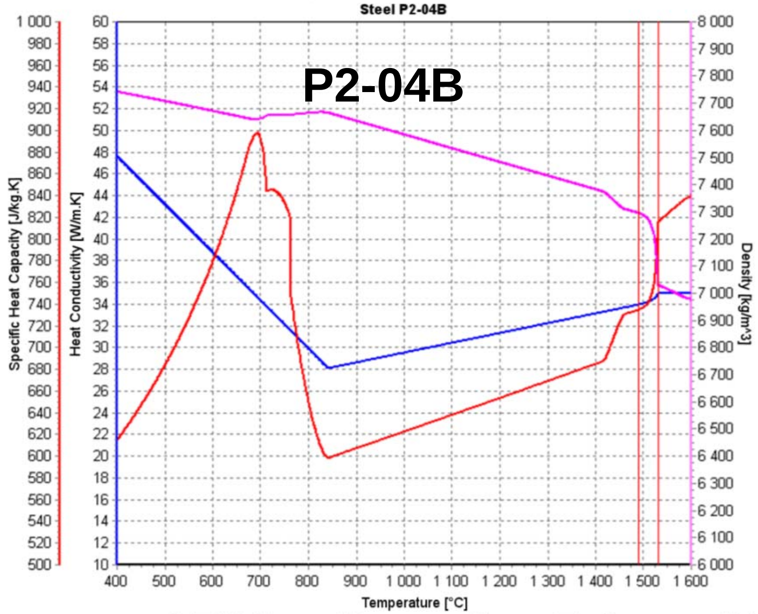
$$T_{i,j,k}^{(\tau+\Delta\tau)} = T_{i,j,k}^{(\tau)} + (QZ1_{i,j} + QZ_{i,j} + QY1_i + QY_i + QX1 + QX)\frac{\Delta\tau}{c_v \cdot \Delta x \cdot \Delta y \cdot \Delta z \cdot \rho}$$

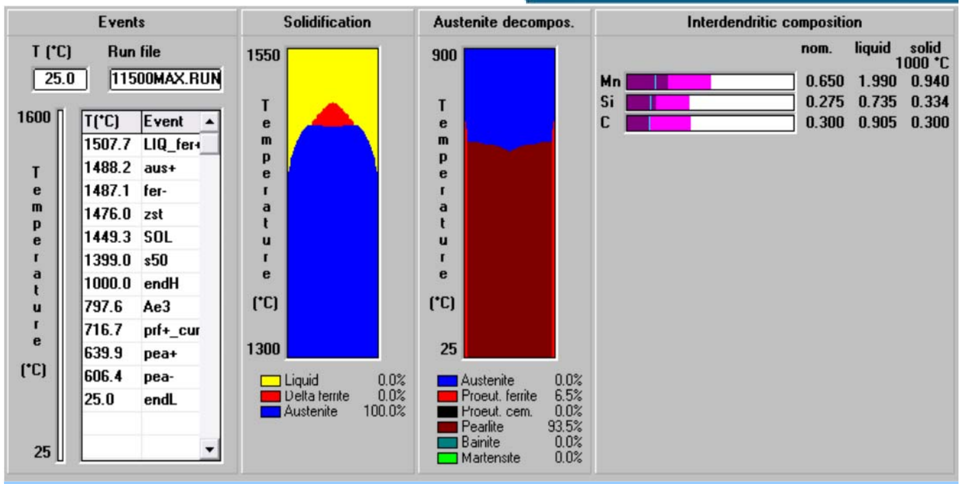
$$H_{i,j,k}^{(\tau+\Delta\tau)} = H_{i,j,k}^{(\tau)} + (QZ1_{i,j} + QZ_{i,j} + QY1_i + QY_i + QX1 + QX)\frac{\Delta\tau}{\Delta x \cdot \Delta y \cdot \Delta z \cdot \rho}$$

MATERIAL PROPERTIES – BILLET STEEL

IDS software

$\rho(T)$ [kg.m^{-3}]	- Density
k (T) [W.m^{-1}.K^{-1}]	- Heat Conductivity
c(T) [J.kg^{-1}.K^{-1}]	- Specific Heat Capacity





We use a solidification analysis package for steels IDS. IDS calculates thermophysical material properties from liquid state to room temperature.

$$T_{Likvidus} = 1536 - 8 \cdot wtC - 7{,}6 \cdot wtSi - 3{,}9 \cdot wtMn - 33{,}4 \cdot wtP - 38 \cdot wtS - 3{,}7 \cdot wtCu - 3{,}1 \cdot wtNi - 1{,}3 \cdot wtCr - 3{,}6 \cdot wtAl$$

$$T_{Solidus} = 1536 - 251 \cdot wtC - 12{,}3 \cdot wtSi - 6{,}8 \cdot wtMn - 123{,}4 \cdot wtP - 183{,}9 \cdot wtS - 3{,}3 \cdot wtNi - 1{,}4 \cdot wtCr - 3{,}1 \cdot wtCr - 3{,}6 \cdot wtAl$$

DATABASE OF STEEL

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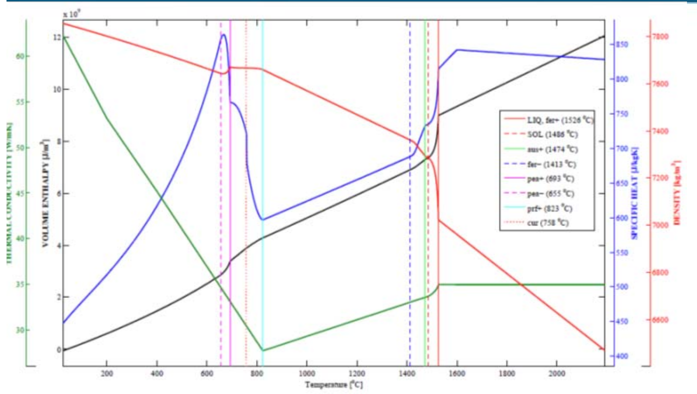
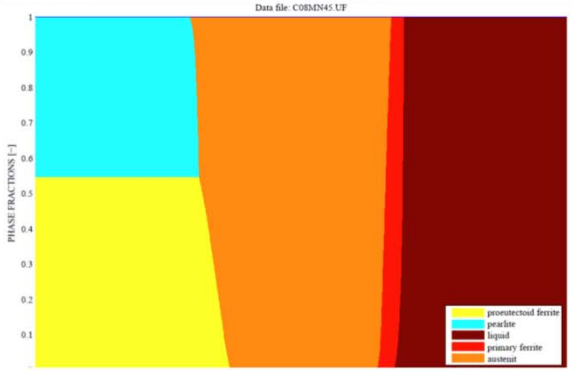
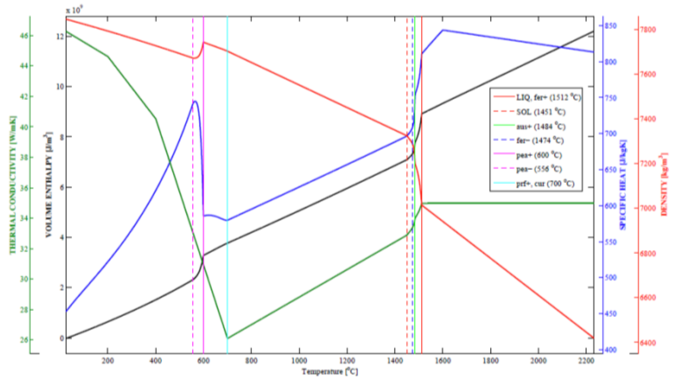
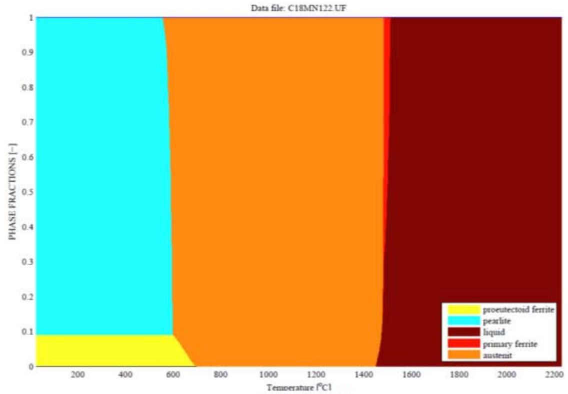
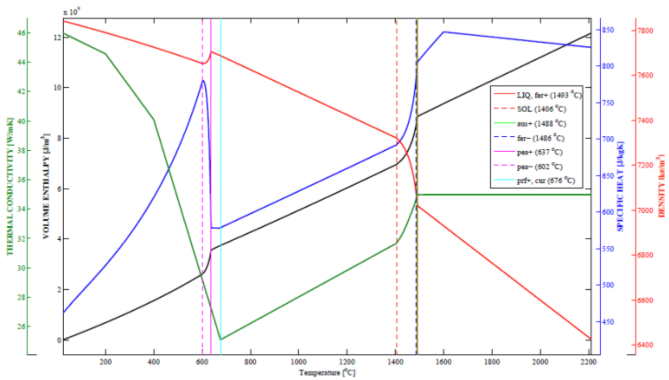
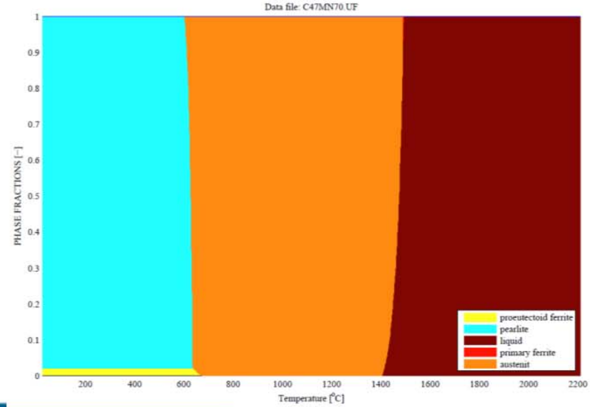




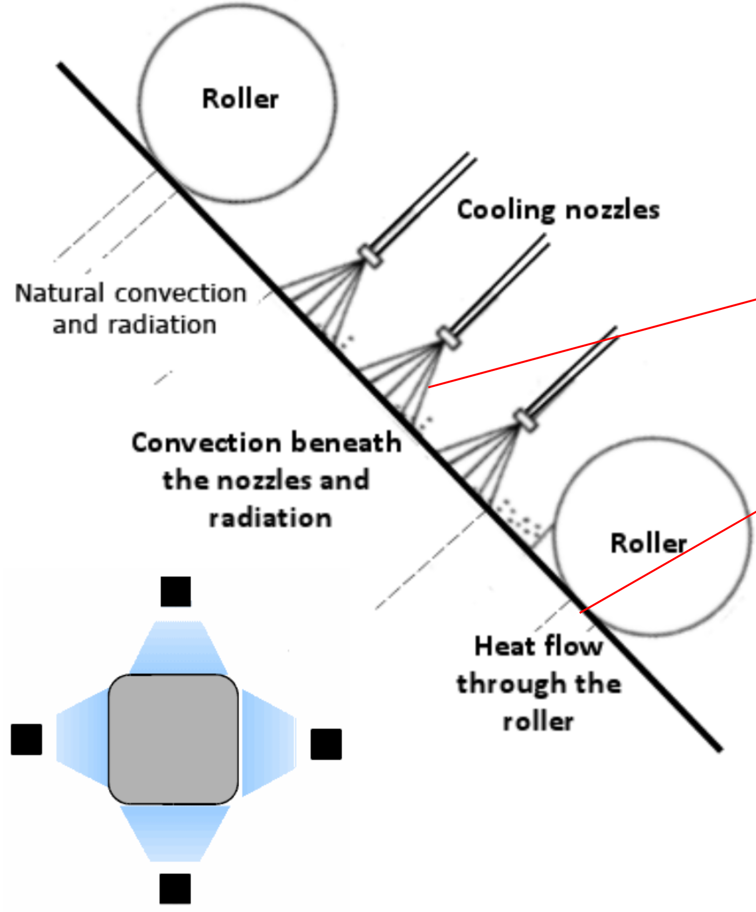




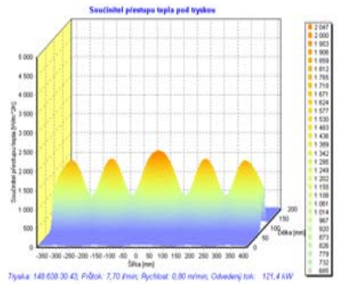




BOUNDARY CONDITIONS



Experiment for each nozzles



$$\dot{Q}_{rol} = htc_{rol} \cdot \pi \cdot \frac{l}{2} \cdot d \cdot (T_{rol} - T_{amb})$$

$$htc_{rol} = htc_{rolnat} + \varepsilon_{rol} \cdot \sigma \cdot (T_{rol}^2 + T_{amb}^2) \cdot (T_{rol} + T_{amb})$$

Natural convection $$htc_{nat} = 0{,}84 \cdot \sqrt{(T_{surface} - T_{amb})}$$

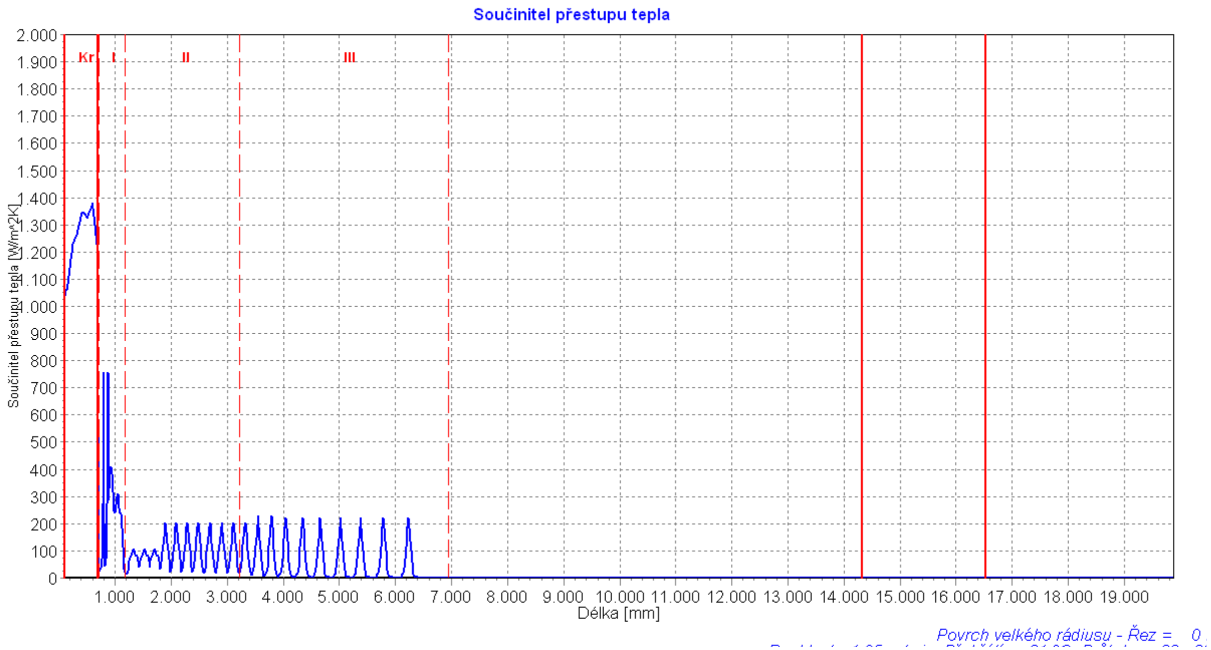
Radiation $$htc_r = \varepsilon \cdot \sigma \cdot (T_{surface}^2 + T_{amb}^2) \cdot (T_{surface} + T_{amb})$$

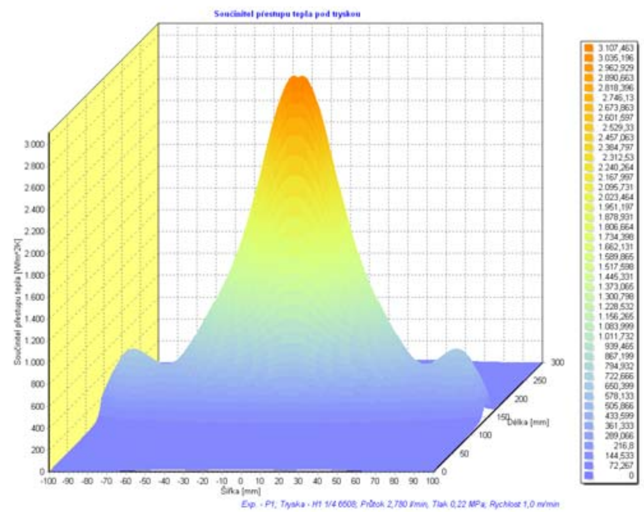
$$\varepsilon = 0{,}78828571429 + 0{,}0003375 \cdot T_{surface} - 40{,}17857143 \cdot 10^{-6} \cdot T_{surface}^2$$

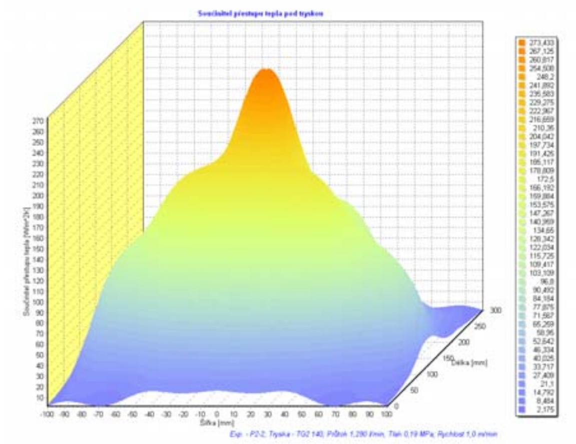
Q [W] *heat flow* ***htc [W.m^{-2}.K^{-1}]*** heat transfer coefficient ***l, d [m]*** *roller dimensions*

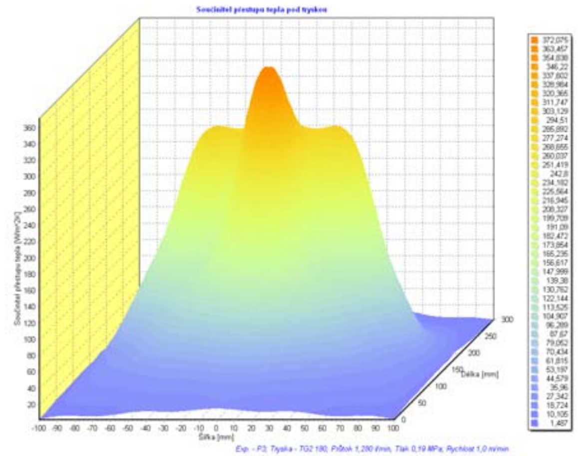
T [K] *temperature* **ε [-]** emissivity

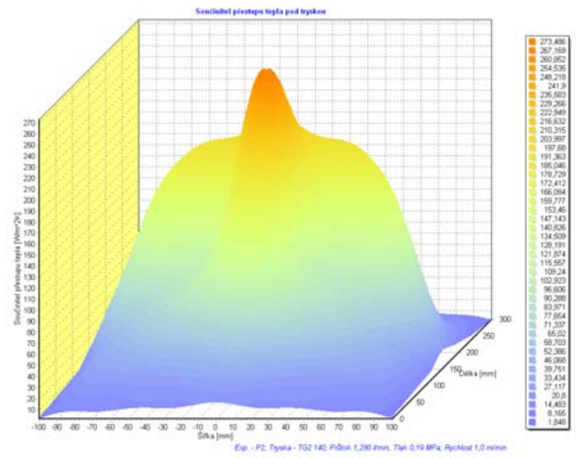
SECONDARY COOLING – BOUNDARY CONDITION





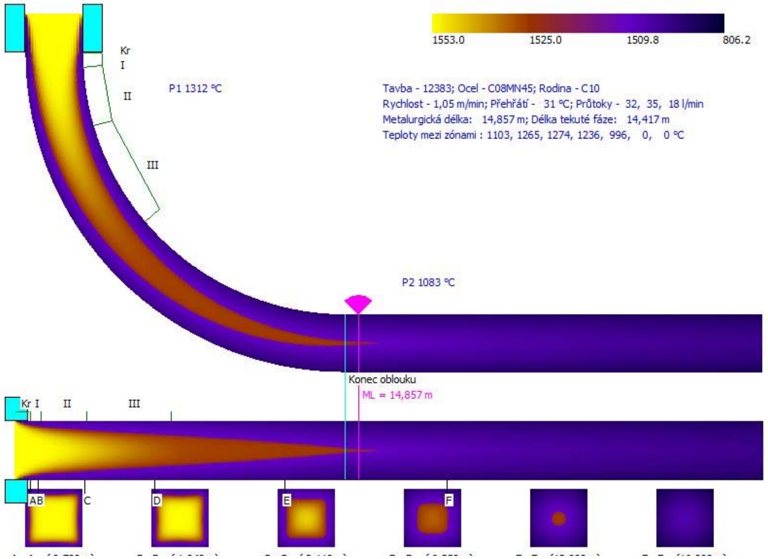


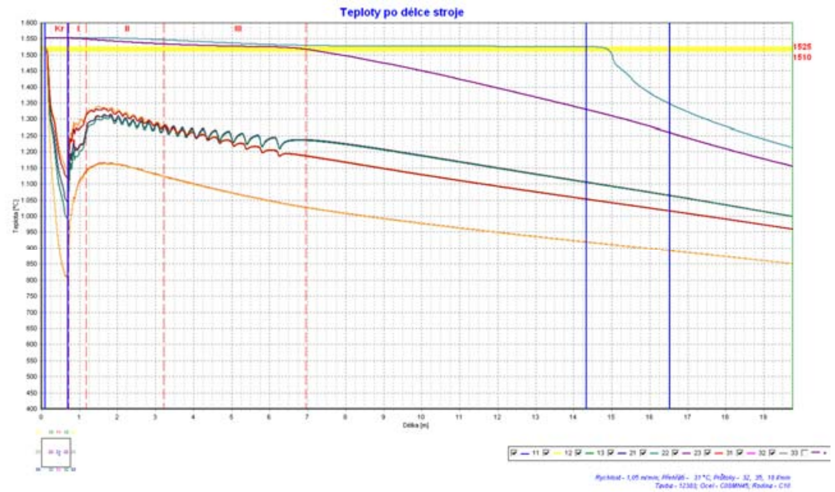




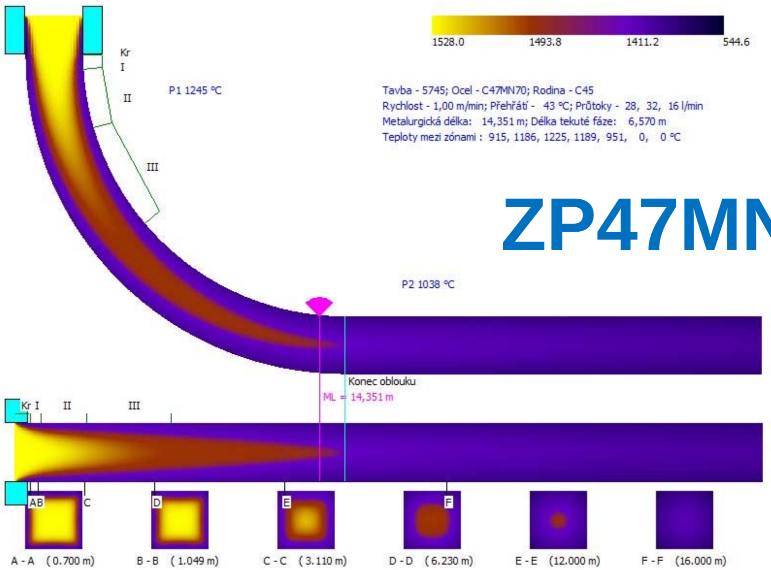
RESULT =TEMPERATURE FIELD

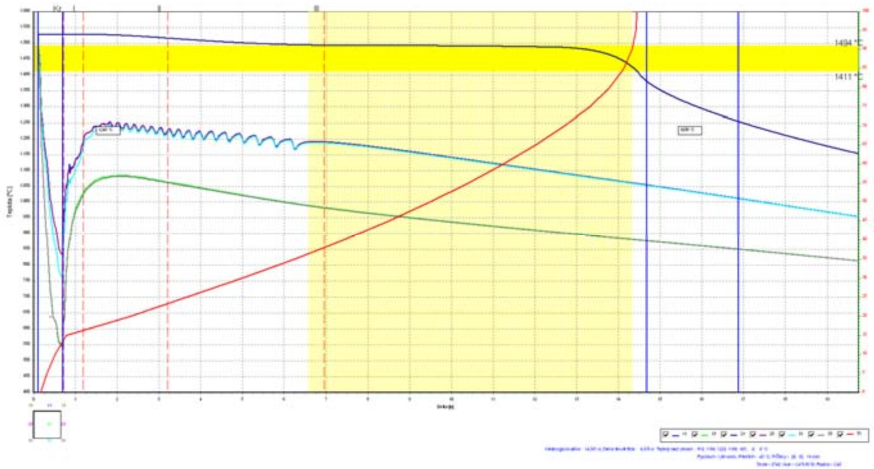
ZP08MN4



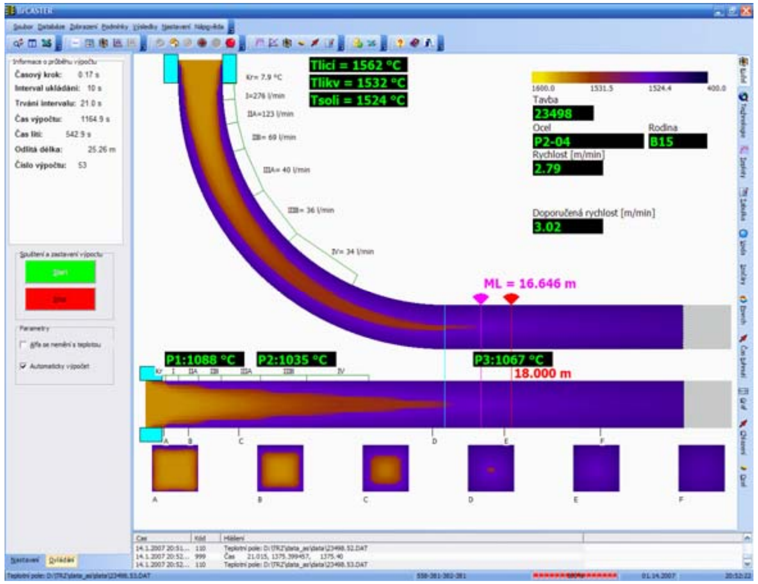


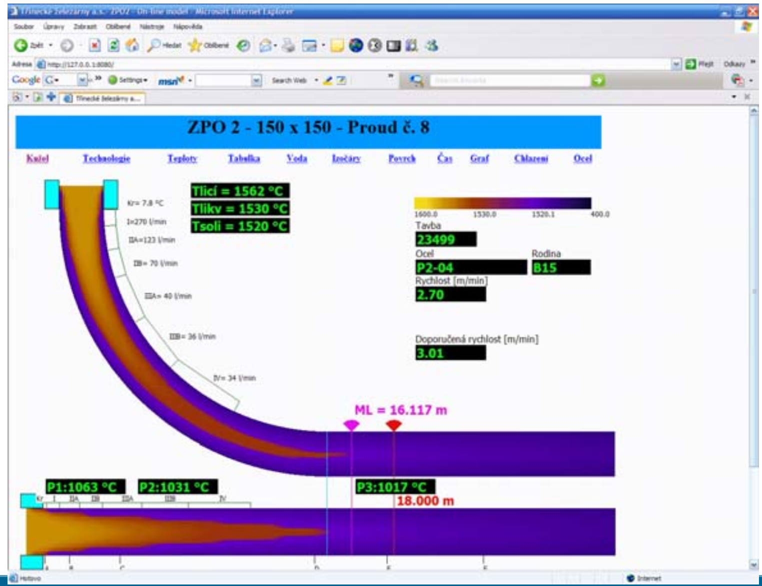
ZP47MN70

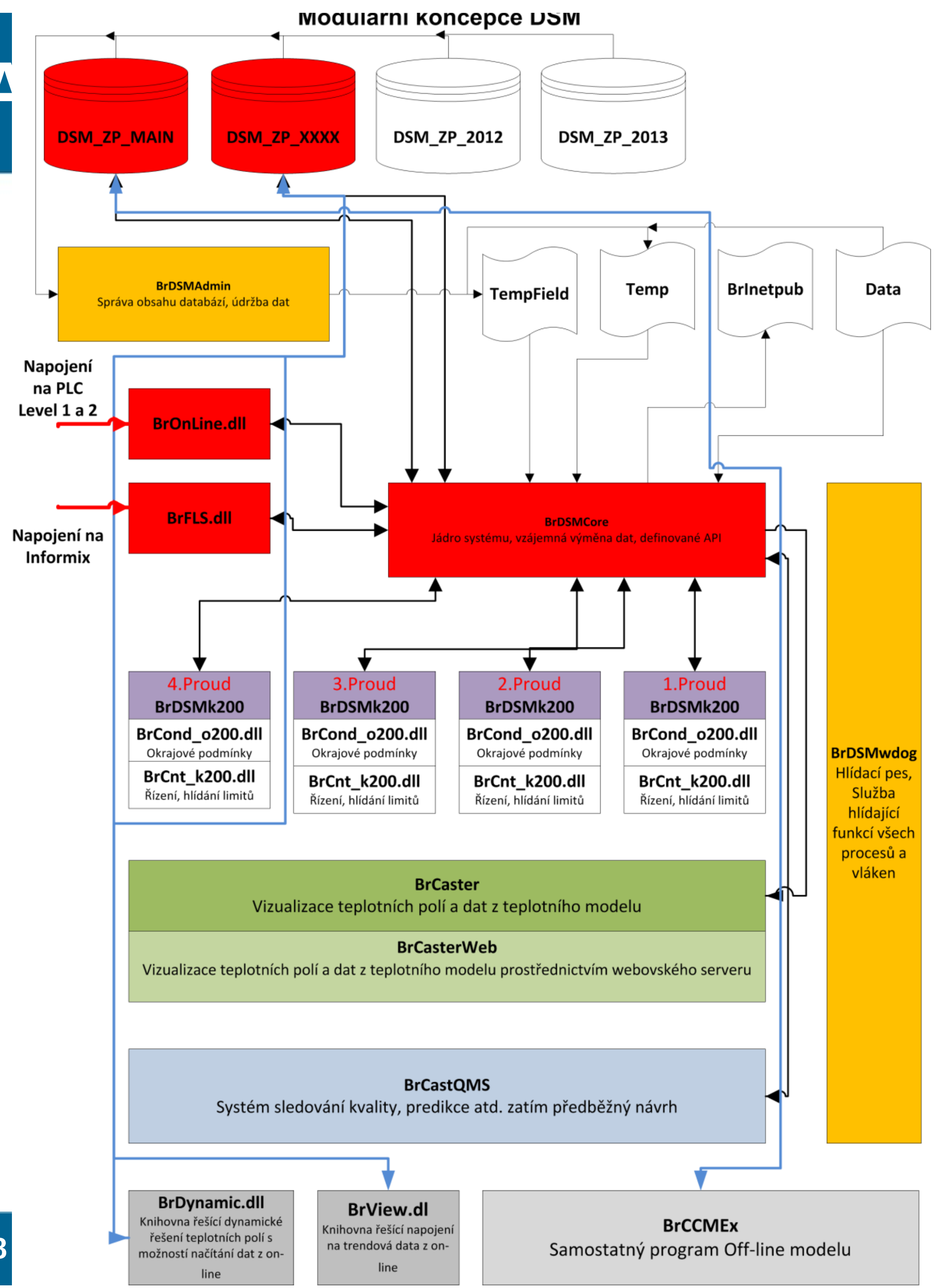




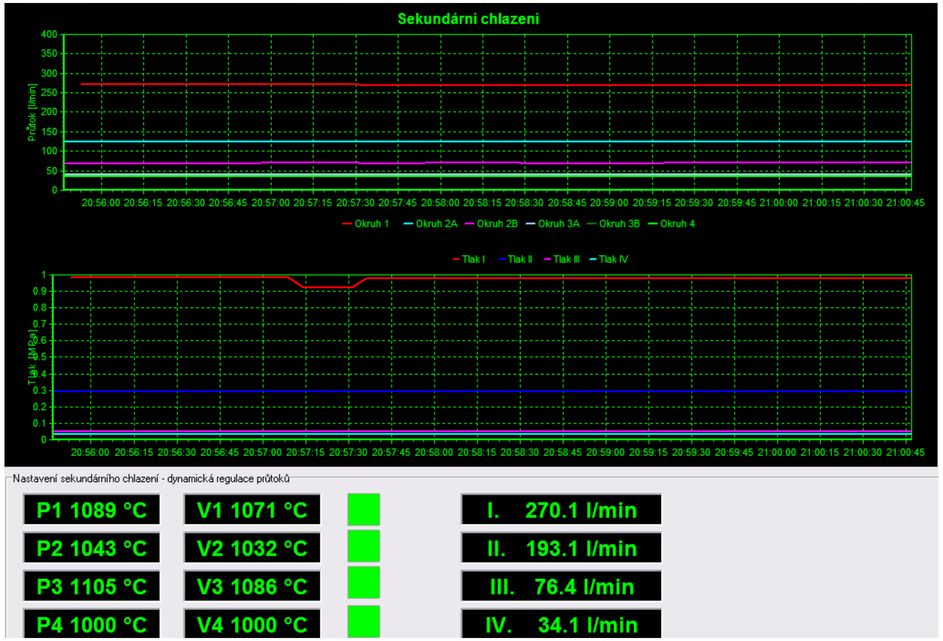
THE METALLURGICA

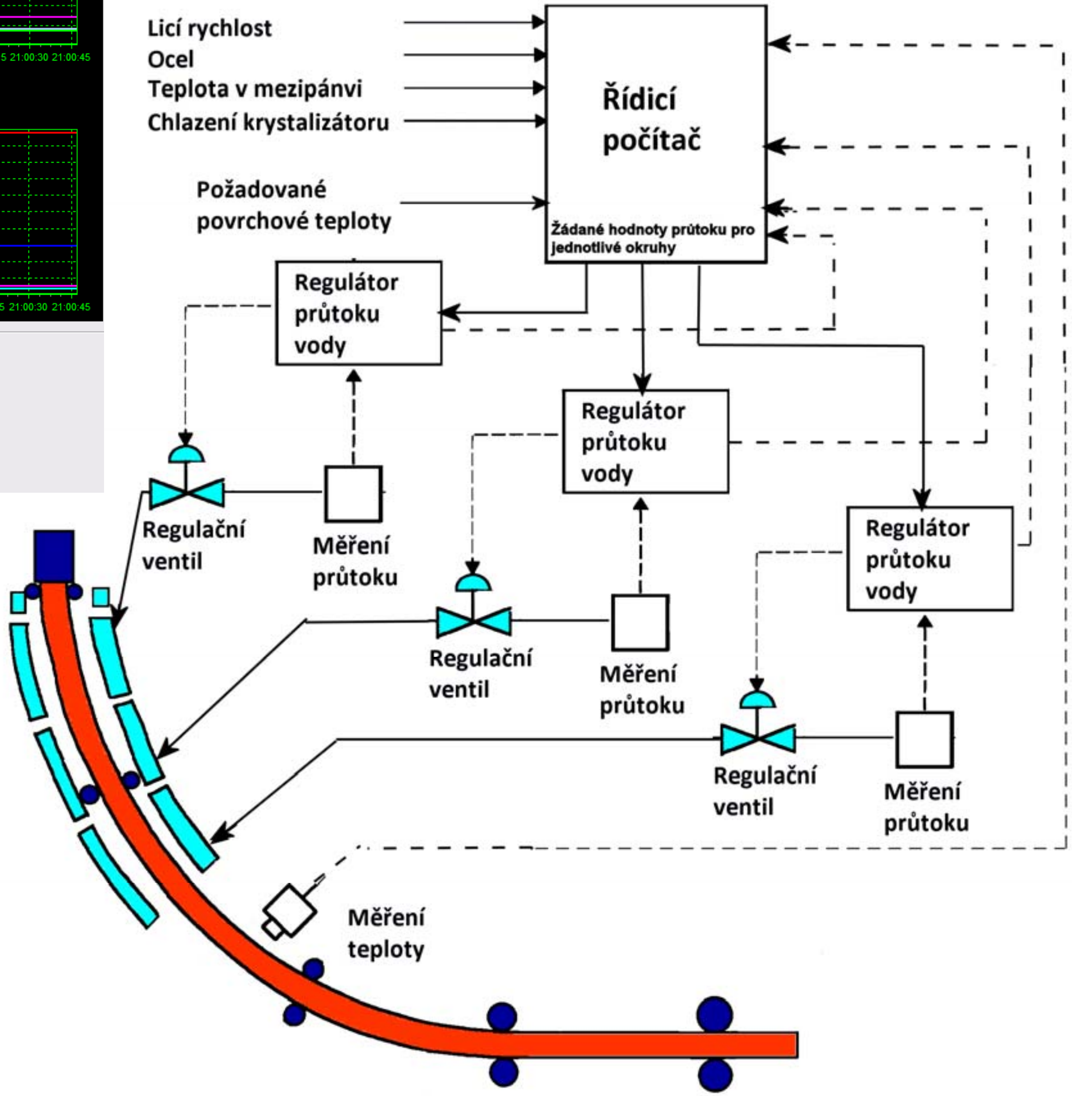






THE EFFECT OF THE SECONDARY COOLING





CLASSIC CONTROLLER VS. MODEL PREDICTIVE CONTROL

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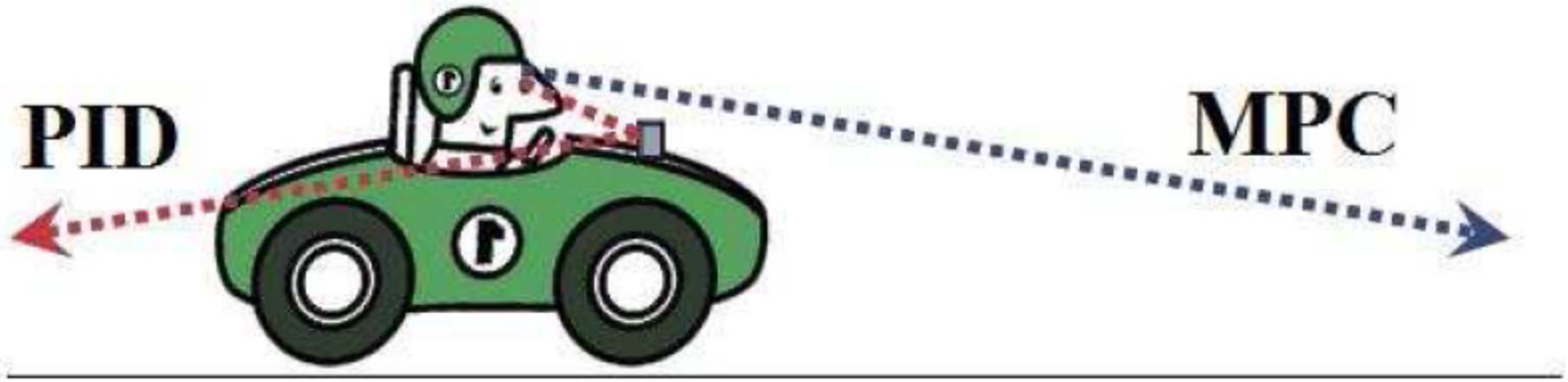
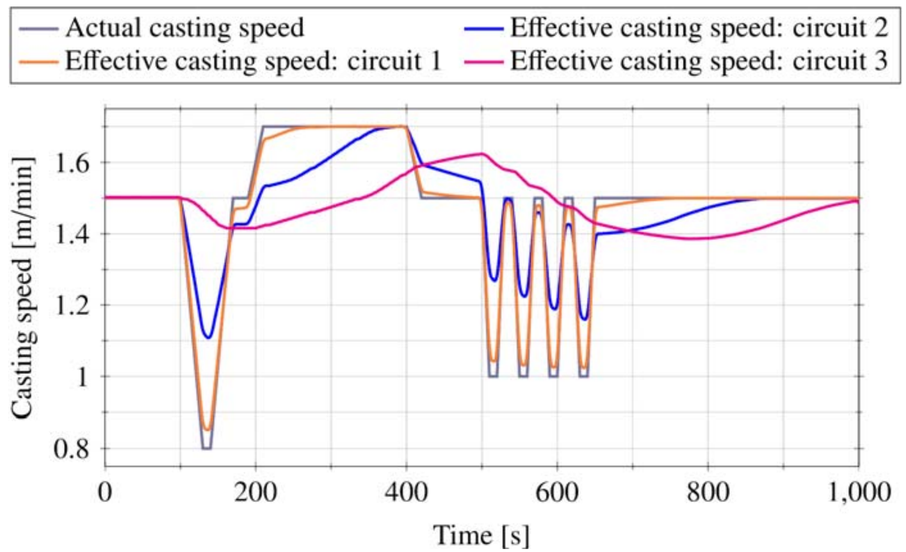
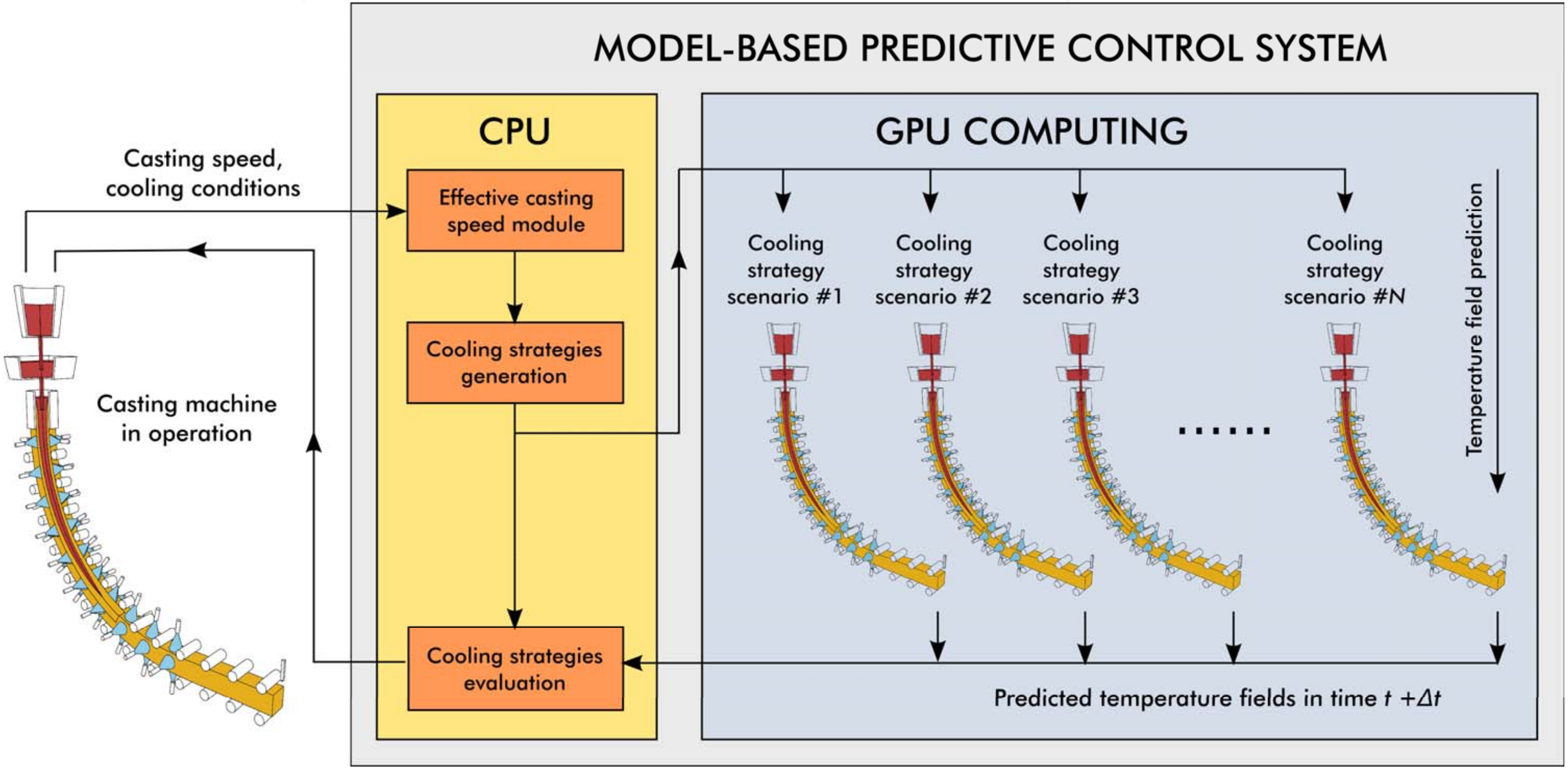




MODEL-BASED PREDICTIVE CONTROL SYSTEM

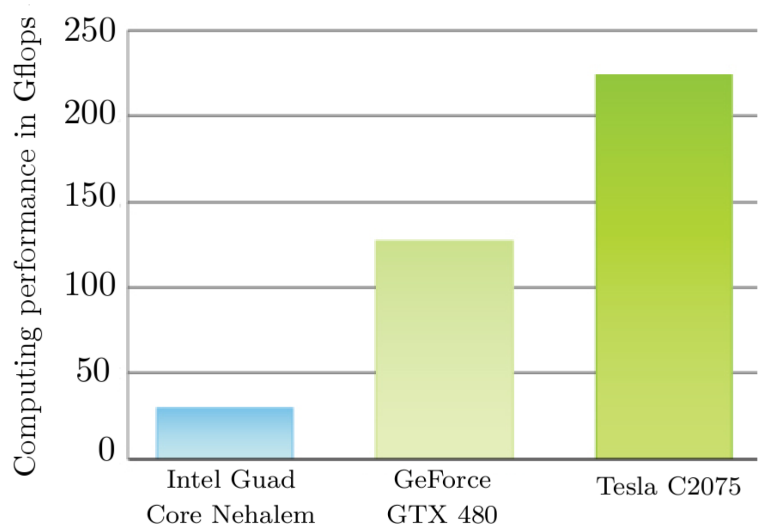


GPGPU COMPUTING

GPGPU = computing on graphics processing units **GPU**

- **huge computing performance**
- scientific and technical computing
- for massively **parallelizable problems**
- Hundreds or even thousands of computing units concurrently running code

COMPUTING GRID	ΔT	CPU TIME	GPU TIME	SPEED-UP
1,000,000	0.60 s	15 min 53 s	24.1 s	40x



CONCLUSION

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- This paper introduces a 3D numerical model of the temperature field for concasting of steel in the form of in-house
- The model includes the main thermodynamic transfer phenomena during the solidification of concasting.
- Another objective is to apply the model for monitoring these phenomena in real time.
- New computational resources ie GPGPU brings new control capabilities the process of casting
- Model Predictive Control - MPC - use experience as effective casting speed and effective superheat

THANK YOU FOR YOUR ATTENTION.

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