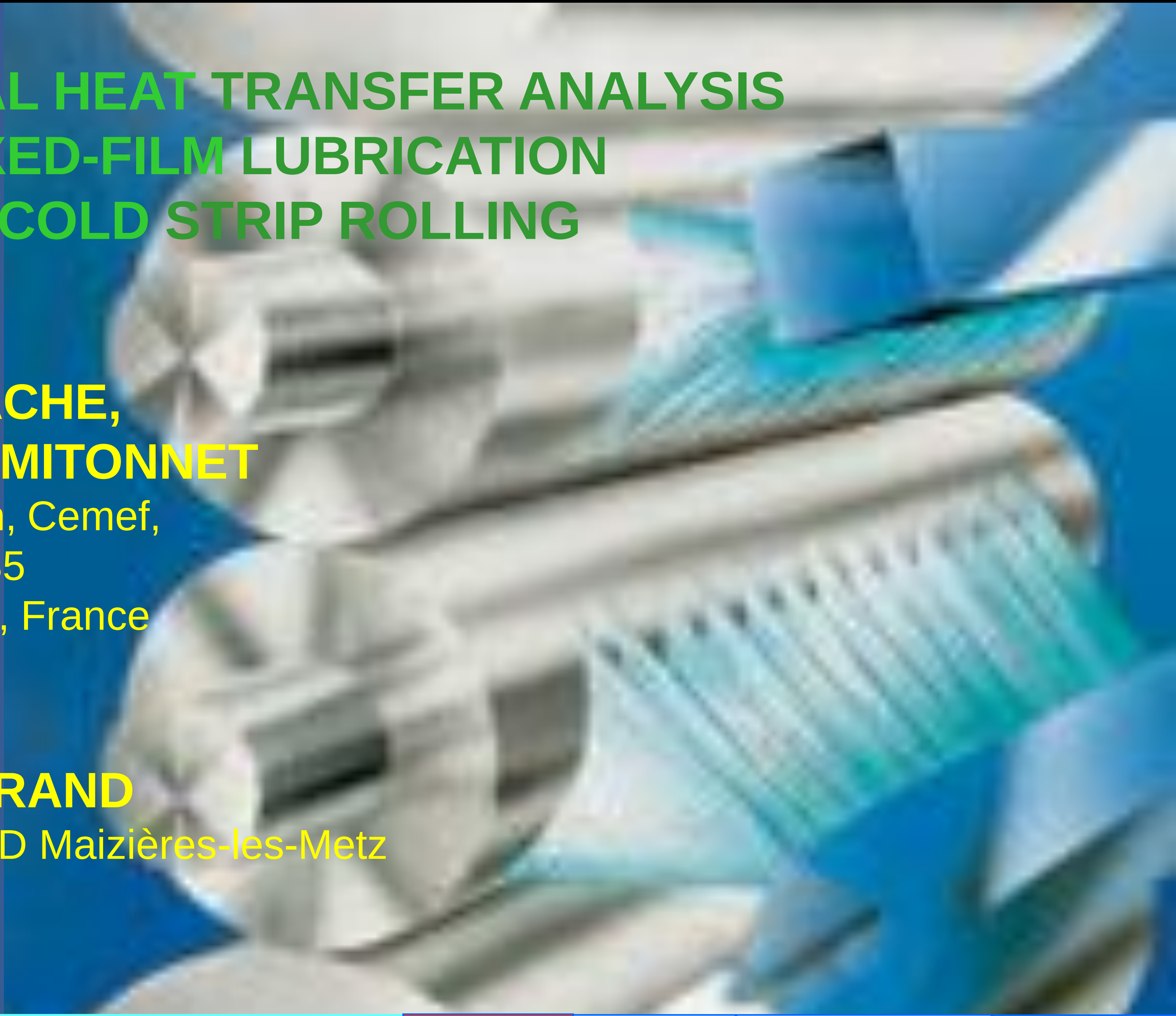
5th European Rolling Conference - ERC 5 – London, UK, June 23-25, 2009



A NUMERICAL HEAT TRANSFER ANALYSIS IN MIXED-FILM LUBRICATION FOR COLD STRIP ROLLING

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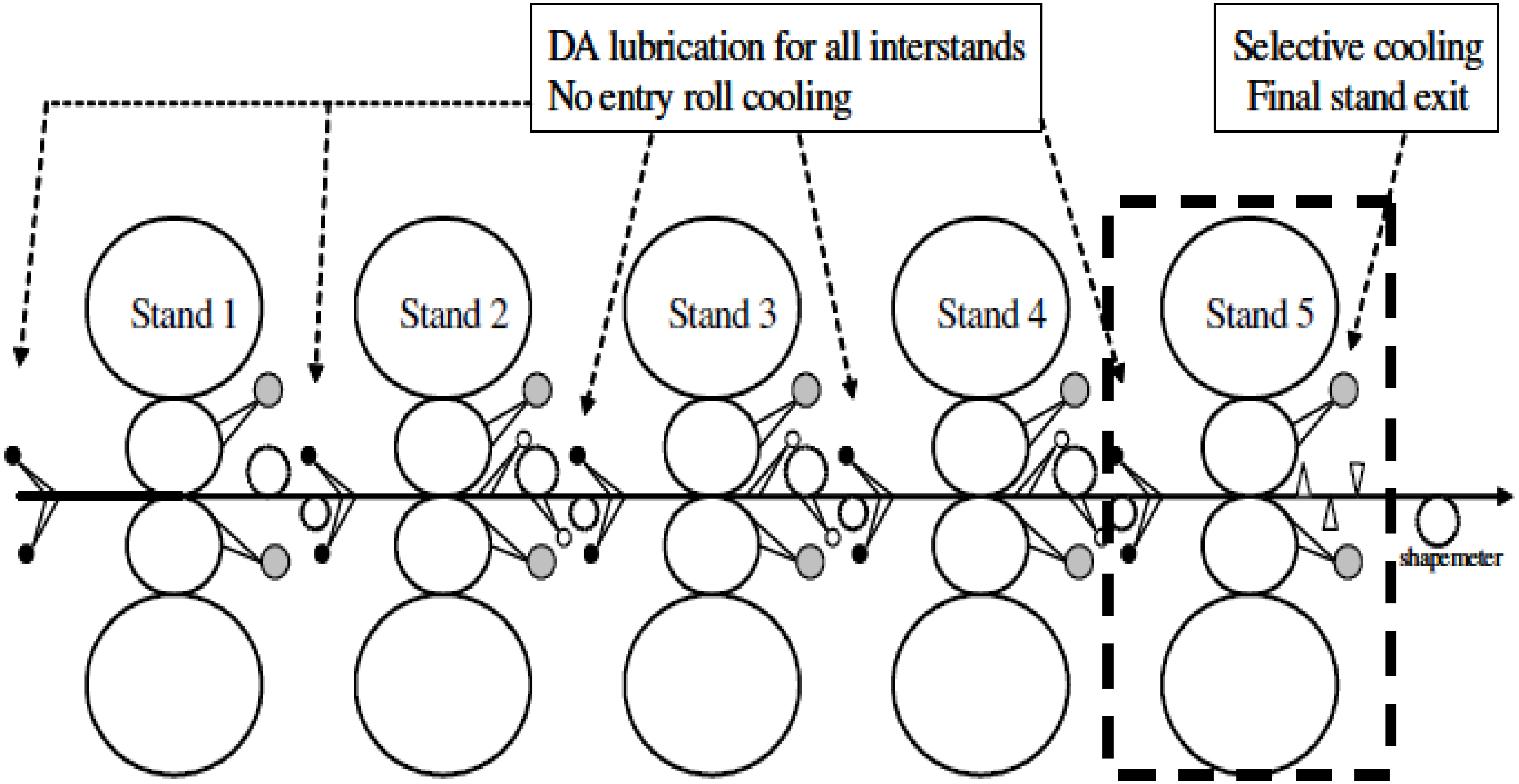
RFCS

OPTCOOLUB
New Cooling Techniques for Enhanced Roll Bite Lubrication in Cold Rolling

ArcelorMittal
LECHLER
BRNO
cnrs dépasser les frontières
CRM



- Excessive lubrication → skidding, chattering…
- Insufficient lubrication → bad surface aspect, high forces and torques, profile and flatness defects…

Lubrication actuators include emulsion output, emulsion temperature and also roll & strip cooling.

What is the sensitivity of friction to the latter actuator ?

Summary

Summary

1 – 2D, steady-state thermal modelling

2 – Mixed Lubrication model

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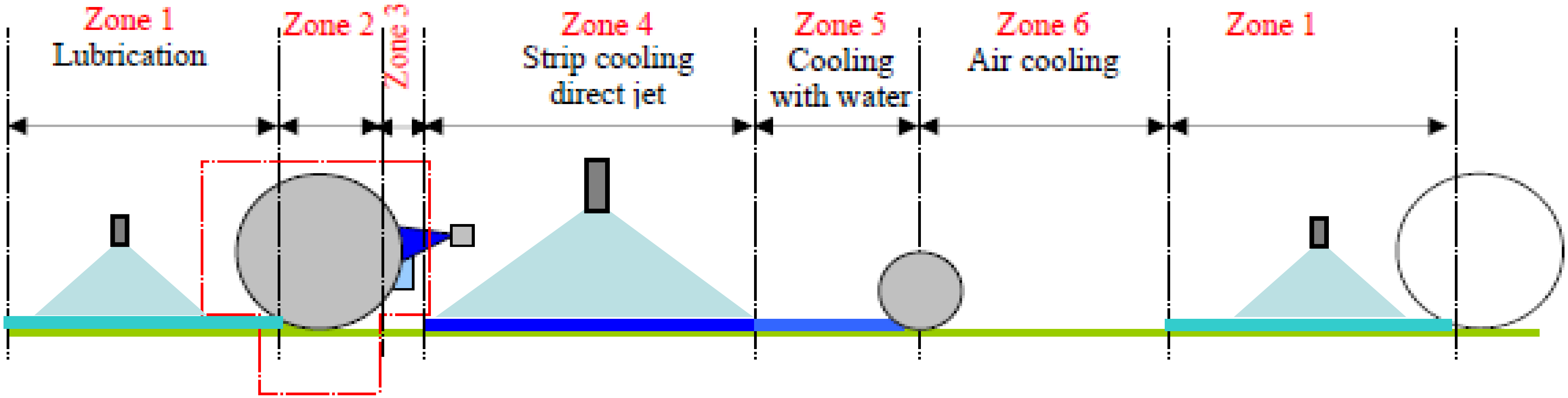
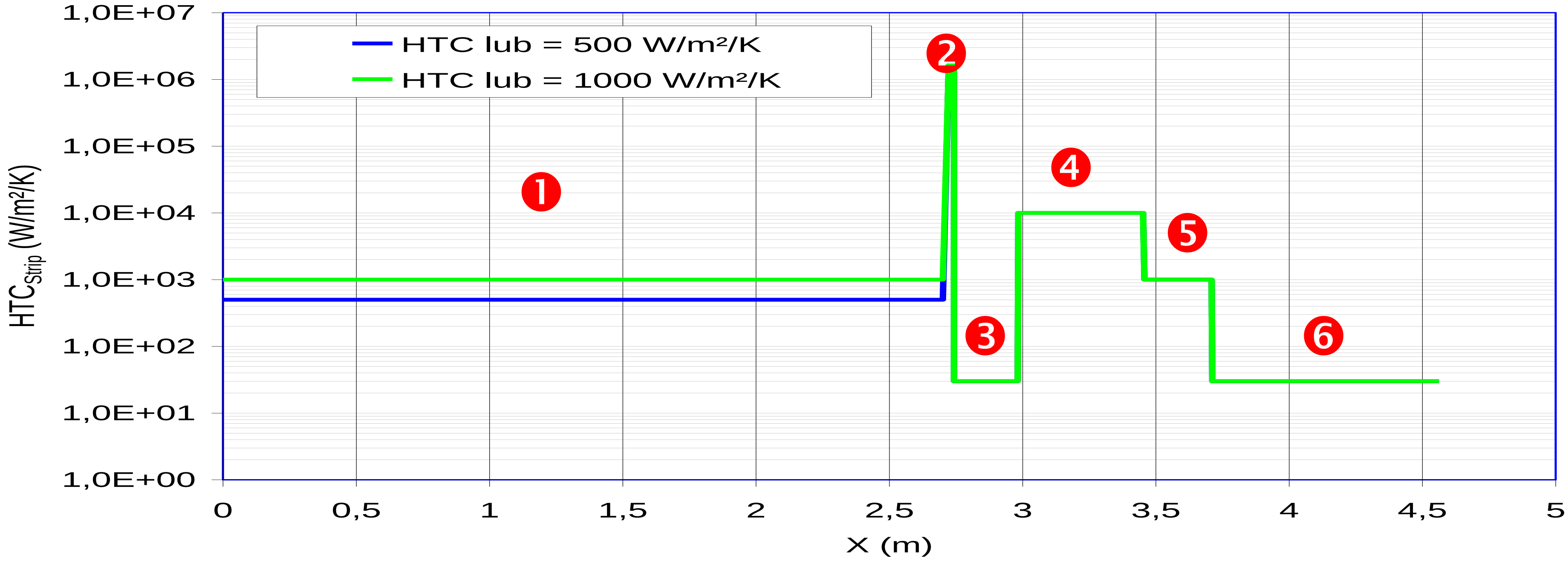
5 – Conclusions

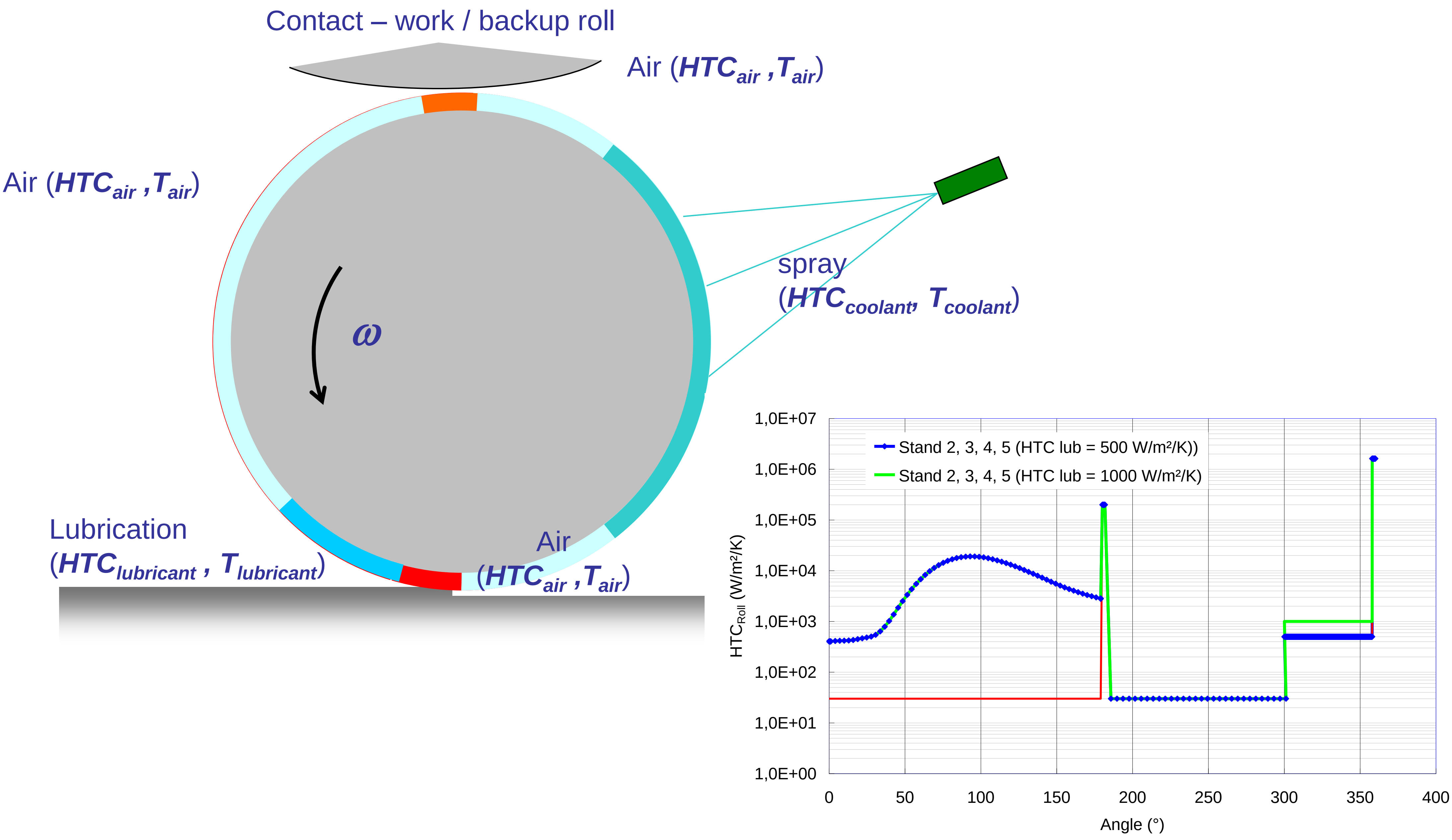
Physical modelling: strip cooling

The model tries to take into account all solid / solid or fluid / solid heat exchanges





Physical modelling: roll cooling



Contact – work / backup roll

Air (HTC_{air} ,T_{air})

Air (HTC_{air} ,T_{air})

ω

spray
($HTC_{coolant}$, $T_{coolant}$)

Lubrication
($HTC_{lubricant}$, $T_{lubricant}$)

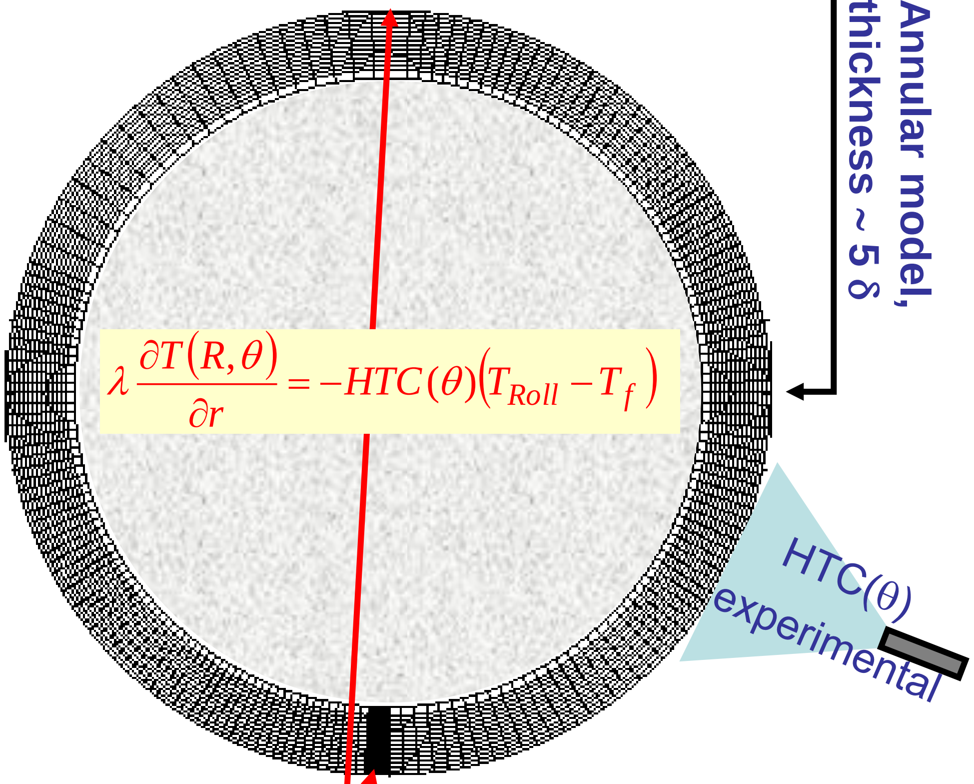
Air
(HTC_{air} ,T_{air})

Numerical modelling

The Roll : explicit 2D FVM

Boundary layer situation $\delta=\frac{R}{\sqrt{Pe}}=\sqrt{\frac{a}{\omega}}$

Annular model, thickness ~ 5 δ



$$\lambda\frac{\partial T(R,\theta)}{\partial r}=-HTC(\theta)\left(T_{Roll}-T_f\right)$$

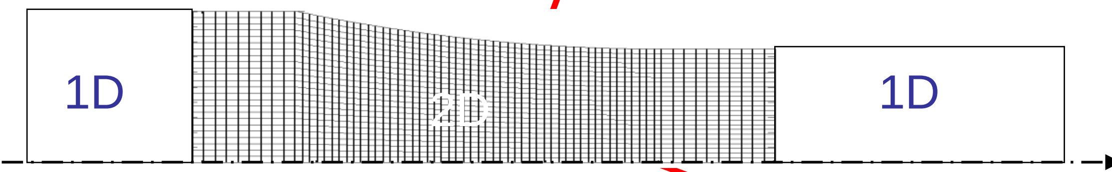
HTC(θ) experimental

$$HTC_{contact}=3800\cdot\frac{2\lambda_{Roll}\lambda_{Strip}}{\lambda_{Roll}+\lambda_{Strip}}\cdot R_q^{-0.257}\left[\frac{P}{P+3.\sigma_0}\right]^{0.94}+\left(\frac{\lambda_{Lub}}{h}\right)(1-A)$$

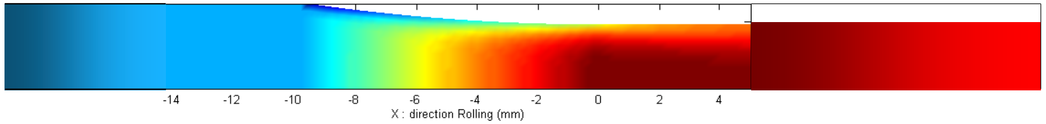
Order of magnitude: a few 10^6 W.m^{-2}.K^{-1}

The Strip : 2D FVM / 1D analytical

$$-HTC(x)\left[T_{Strip}-T_{Roll}\right]+\boxed{(1-\alpha)\tau(x)V_g(x)}$$



$$\rho c\left(u(x)\frac{\partial T_{Strip}}{\partial x}+v(x)\frac{\partial T_{Strip}}{\partial y}\right)=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T_{Strip}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T_{Strip}}{\partial y}\right)+\boxed{0.9\cdot\sigma_0(x)\cdot\dot{\varepsilon}(x)}$$



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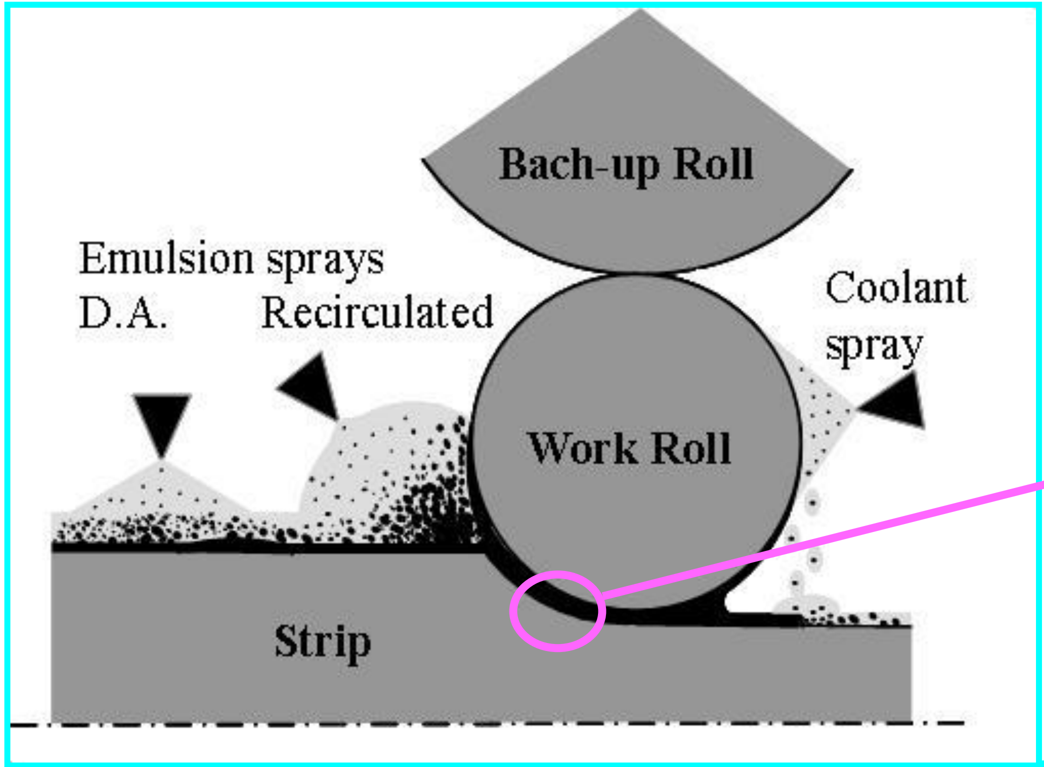
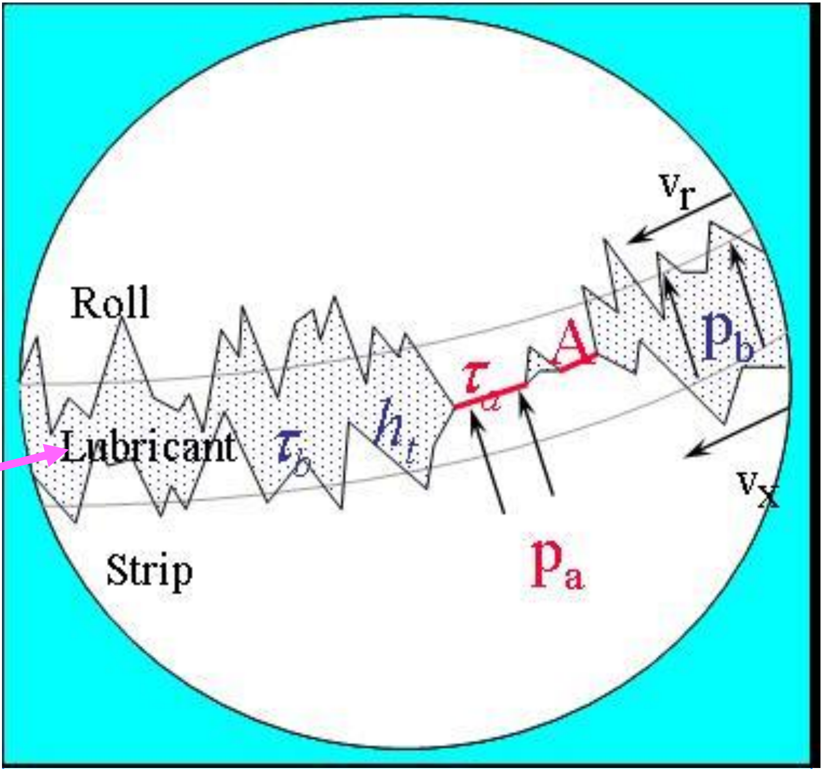
The mixed lubrication / strip rolling model *(rough surfaces, oil lubrication, starvation)*



Model of the interface...



$$p(x) = (1-A(x)).p_b(x) + A(x).p_a(x)$$
$$\tau(x) = (1-A(x)).\tau_b(x) + A(x).\tau_a(x)$$

Macroscopic strip mechanical equilibrium :

$$\frac{d(\sigma_x t)}{dx} = -p\frac{dt}{dx} - 2\tau$$

Elastic-plastic constitutive equations :

$$\frac{\dot{s}}{2\mu} + \frac{3}{2}.\frac{\dot{\bar{\varepsilon}}^{pl}}{\sigma_0}.s = \dot{\varepsilon}$$

$$\dot{p} = -(\lambda + \frac{2}{3}\mu).Tr(\dot{\varepsilon})$$

Roll elastic deformation (influence functions)

$$\delta_i = \sum_j G_{ij}.p_j$$

$$\phi_{p,x}(h).\frac{h^3}{12\eta}.\frac{dp}{dx} = \frac{V_x + V_{roll}}{2}.h_t + \frac{V_x - V_{roll}}{2}.\sigma_{RMS}.\phi_s(h) - Q_{oil}$$

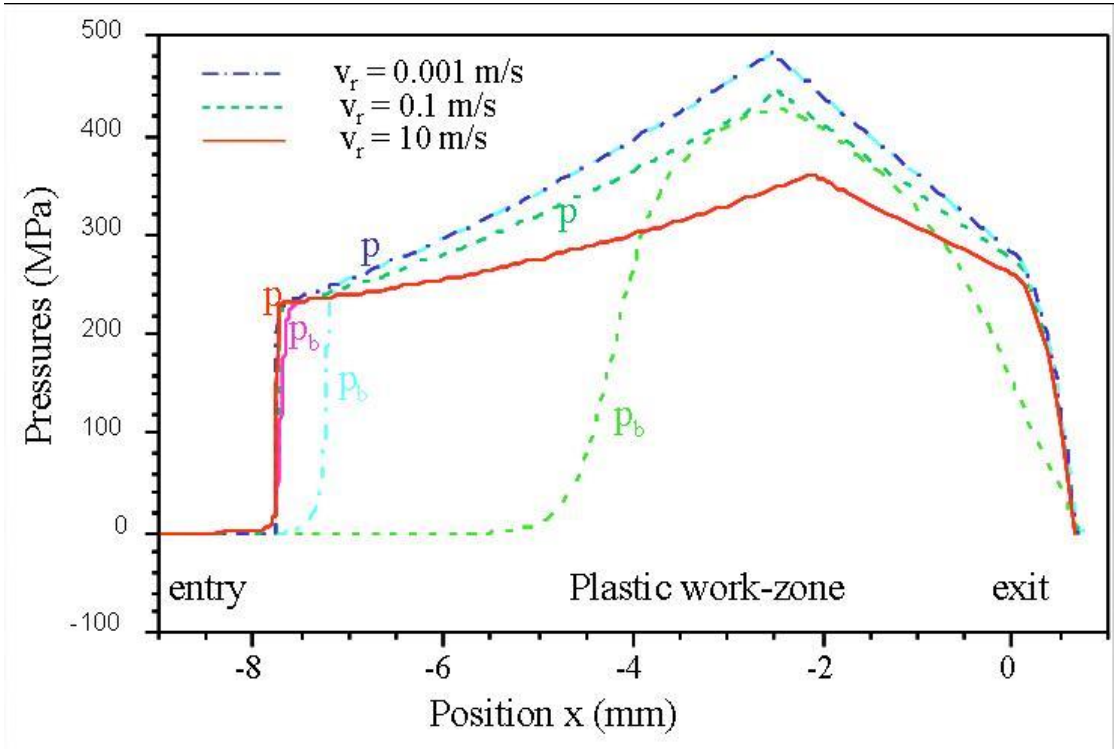
$$H_a = \frac{p_a - p_b}{k_0} = H_a(A, E_p[\dot{\varepsilon}_x])$$

$$E_p = -\frac{\dot{\varepsilon}_x l}{v_a + v_b}$$

$$\frac{dA}{dx} = \frac{\dot{\varepsilon}_x l}{v_x E_p}.f(h)$$

Example of results

Strip, Aluminium : 1.0 → 0.7 mm, σ_0 = 200 MPa, no tensions
Strip + roll roughness: σ_{RMS} = 0.5 µm, longitudinal, pitch = 30 µm
Roll, Steel: R_0 = 200 mm, 10^{-3} < speed v_r < 10^2 m/s
Oil viscosity: η (Pa.s) = 0.01 exp($10^{-8} p_b$)
Boundary friction: m_a = 0.25



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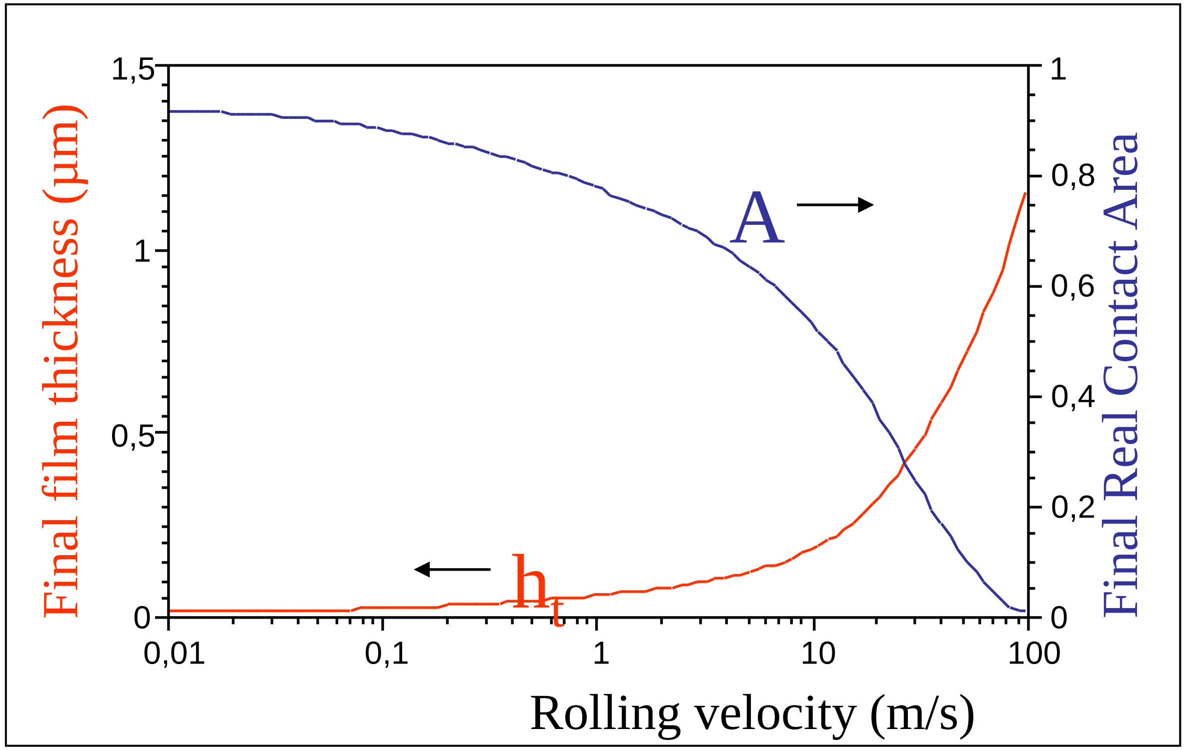

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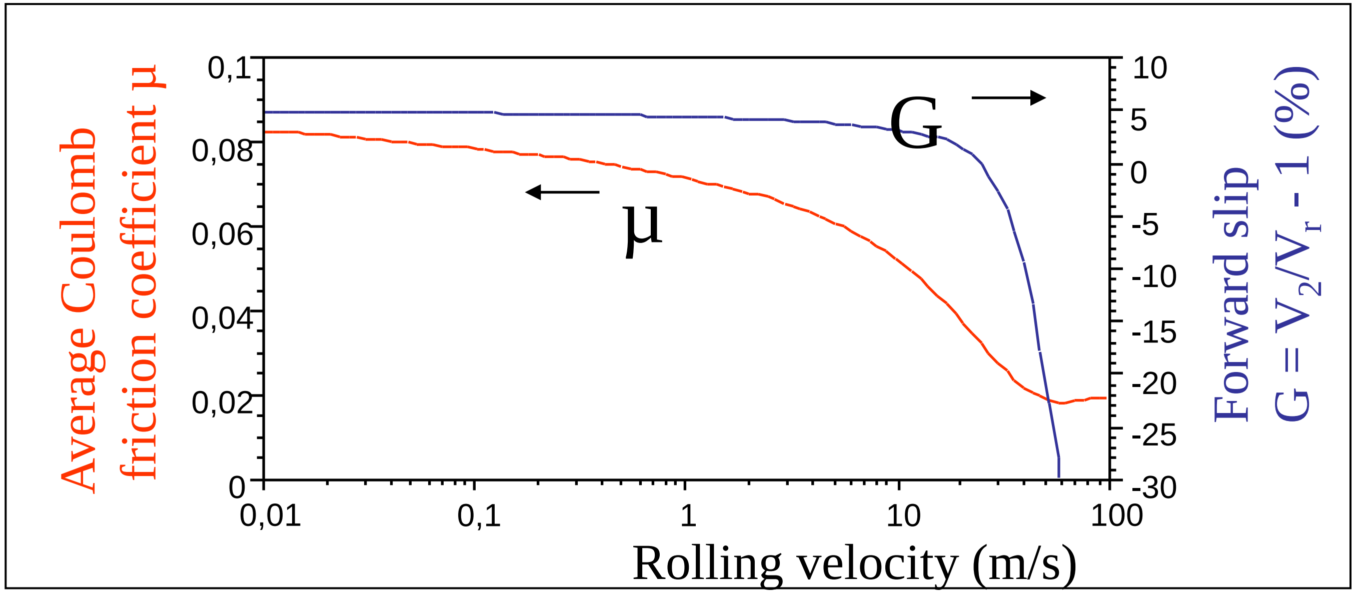
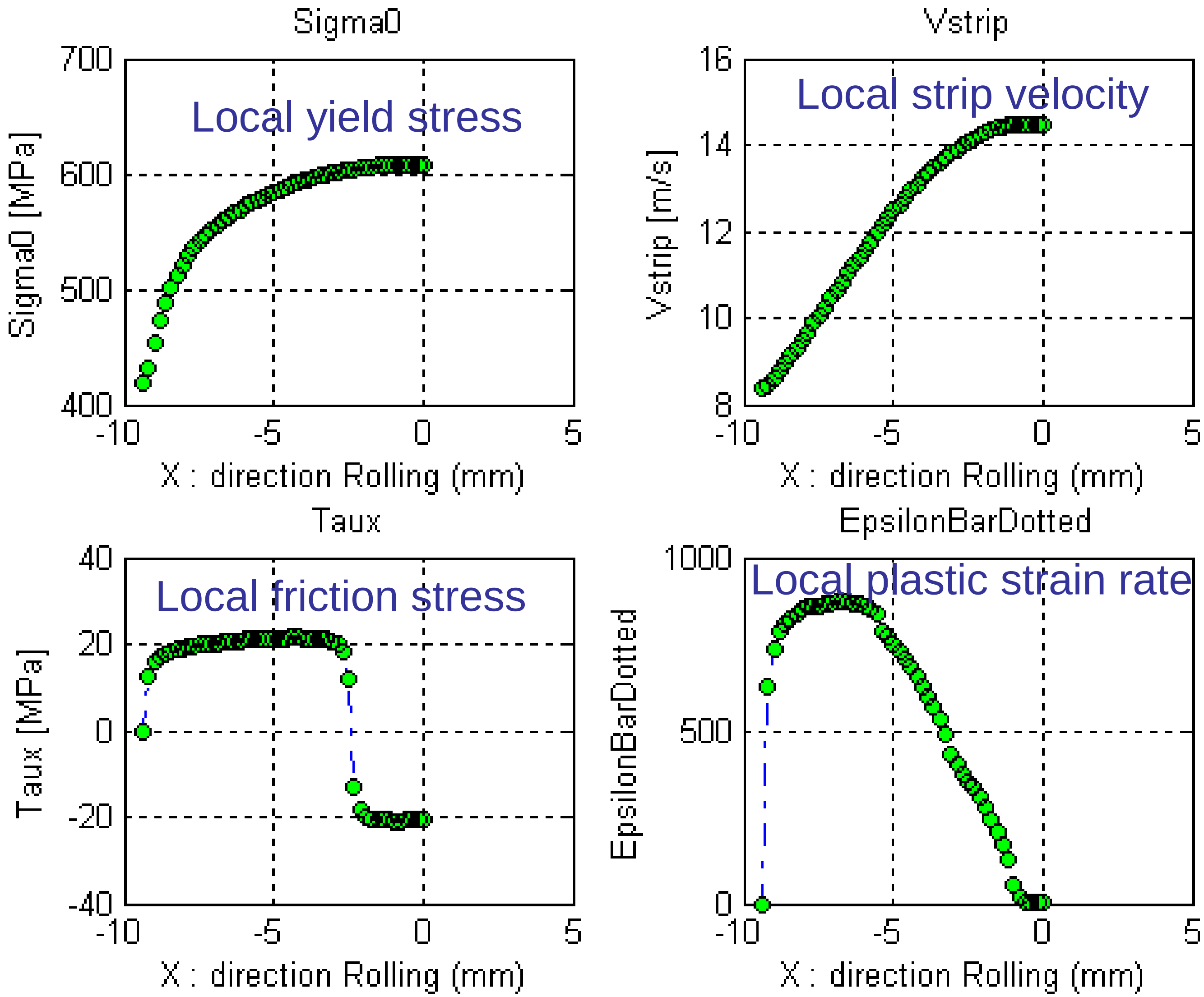


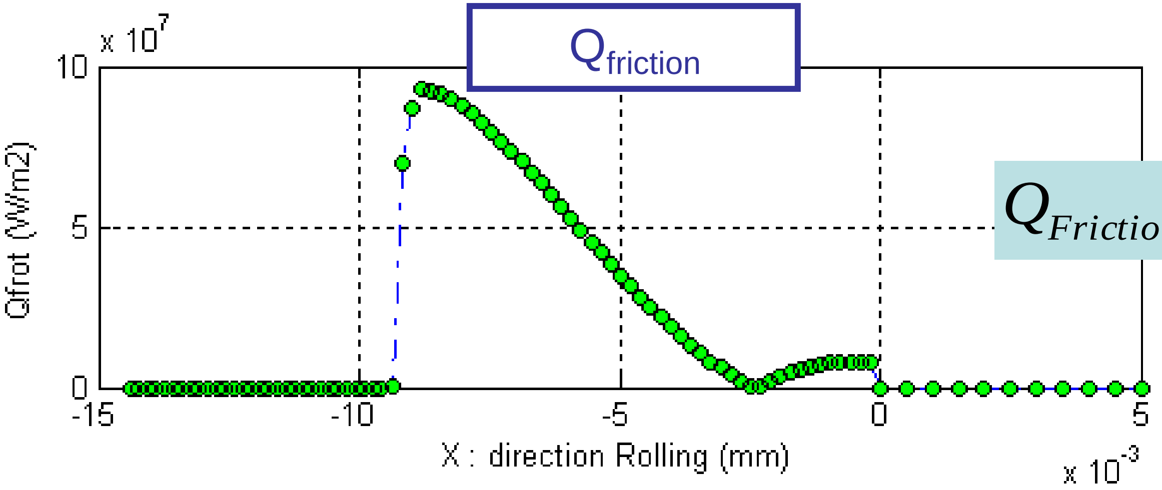


Local yield stress

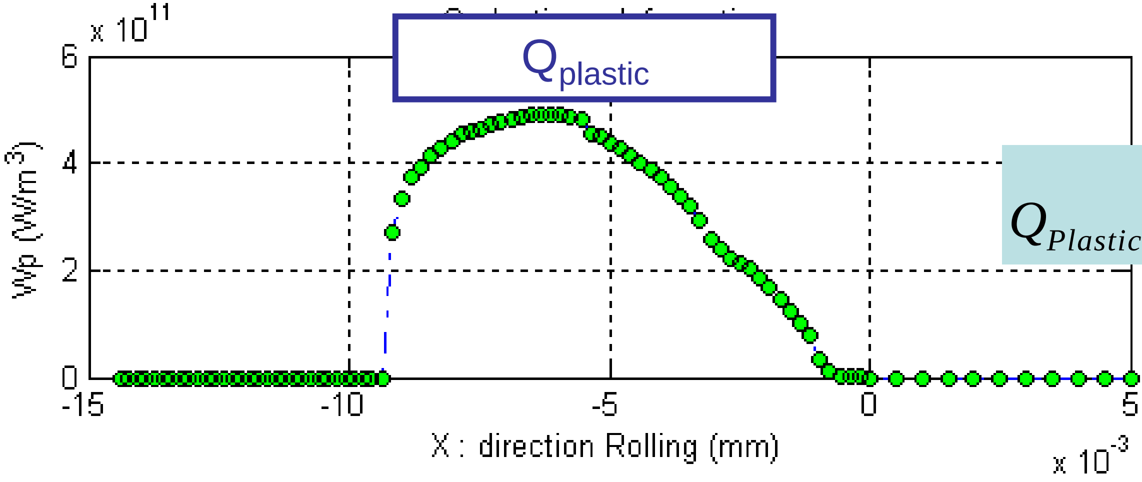
Local strip velocity

Local friction stress

Local plastic strain rate

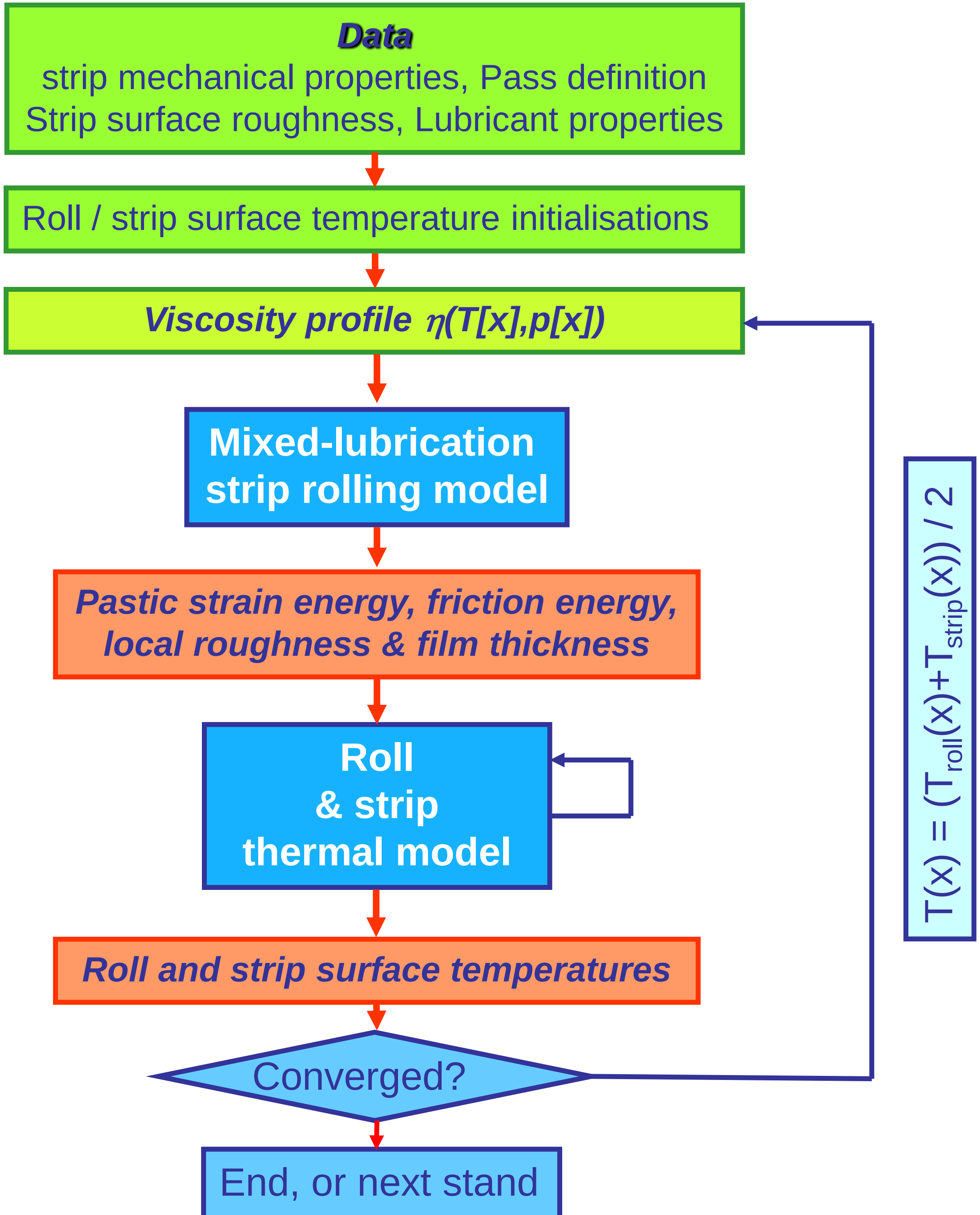


$$Q_{Friction}(x) = \tau(x)V_g(x)$$



$$Q_{Plastic}(x) = 0.9 \cdot \sigma_0(x) \cdot \dot{\varepsilon}(x)$$

Global model outline (1 stand)



Data
strip mechanical properties, Pass definition
Strip surface roughness, Lubricant properties

Roll / strip surface temperature initialisations

Viscosity profile $\eta(T[x],p[x])$

Mixed-lubrication strip rolling model

Pastic strain energy, friction energy, local roughness & film thickness

Roll & strip thermal model

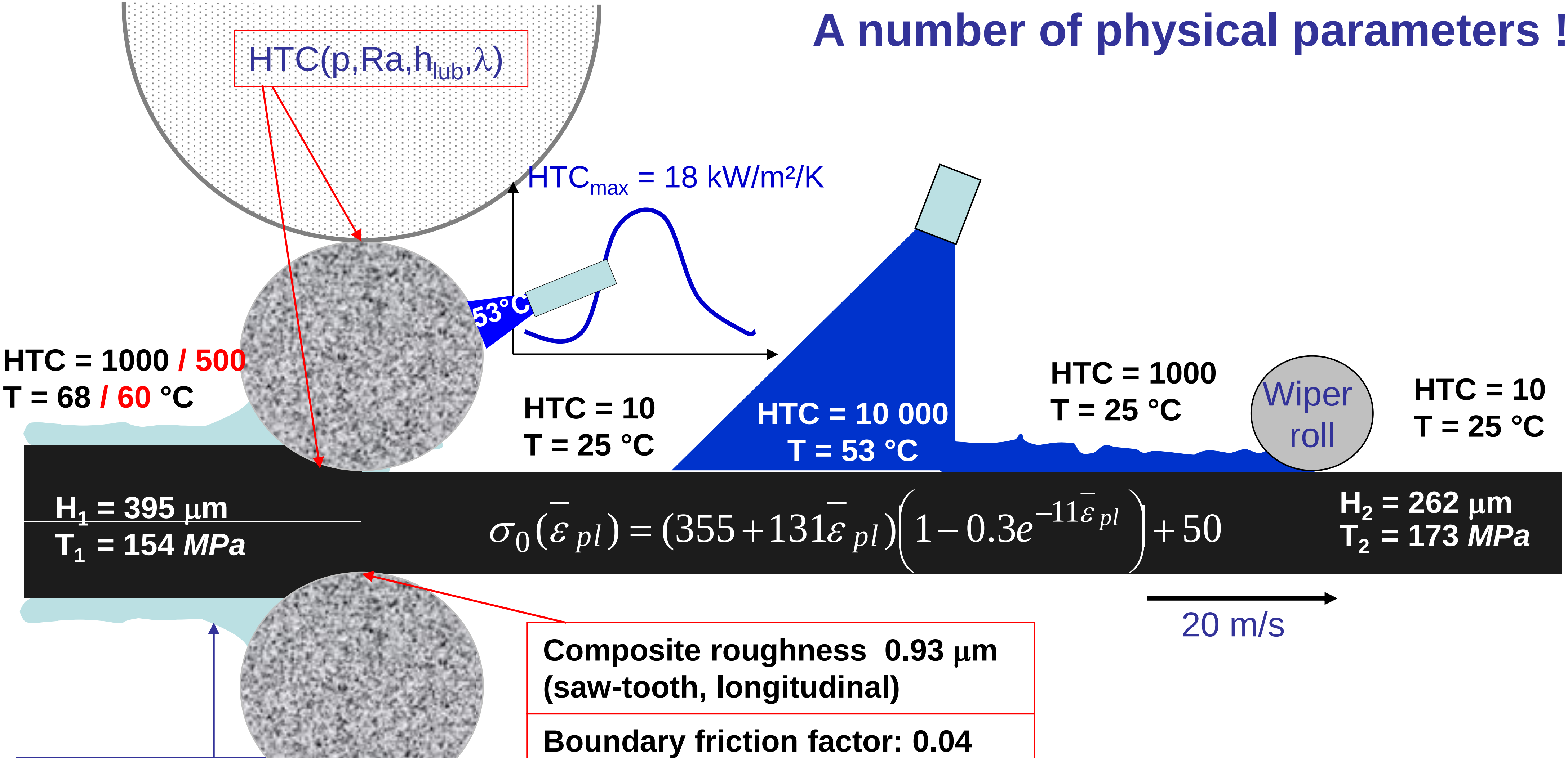
Roll and strip surface temperatures

Converged?

End, or next stand

$T(x) = (T_{roll}(x)+T_{strip}(x)) / 2$

A number of physical parameters !



HTC(p,Ra,h_{lub},λ)

HTC_{max} = 18 kW/m²/K

53°C

HTC = 1000 / 500
T = 68 / 60 °C

HTC = 10
T = 25 °C

HTC = 10 000
T = 53 °C

HTC = 1000
T = 25 °C

Wiper roll

HTC = 10
T = 25 °C

H_1 = 395 µm
T_1 = 154 *MPa*

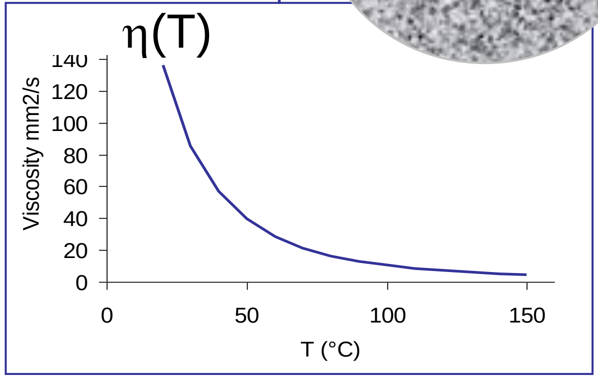
$$\sigma_0(\bar{\varepsilon}_{pl}) = (355 + 131\bar{\varepsilon}_{pl})\left(1 - 0.3e^{-11\bar{\varepsilon}_{pl}}\right) + 50$$

H_2 = 262 µm
T_2 = 173 *MPa*

20 m/s

Composite roughness 0.93 µm (saw-tooth, longitudinal)

Boundary friction factor: 0.04



+

Roelands (p,T) viscosity correlation

$$\ln\left(\frac{\eta(T,p)}{\eta_0}\right) = (\ln\eta_0 + 9.67)\left[\left(1 + \frac{p_f}{196\cdot 10^6}\right) - 1\right]$$

$$\gamma = -\frac{d(Ln\eta)}{dp}\bigg|_{p=0} = 20\,GPa^{-1}$$

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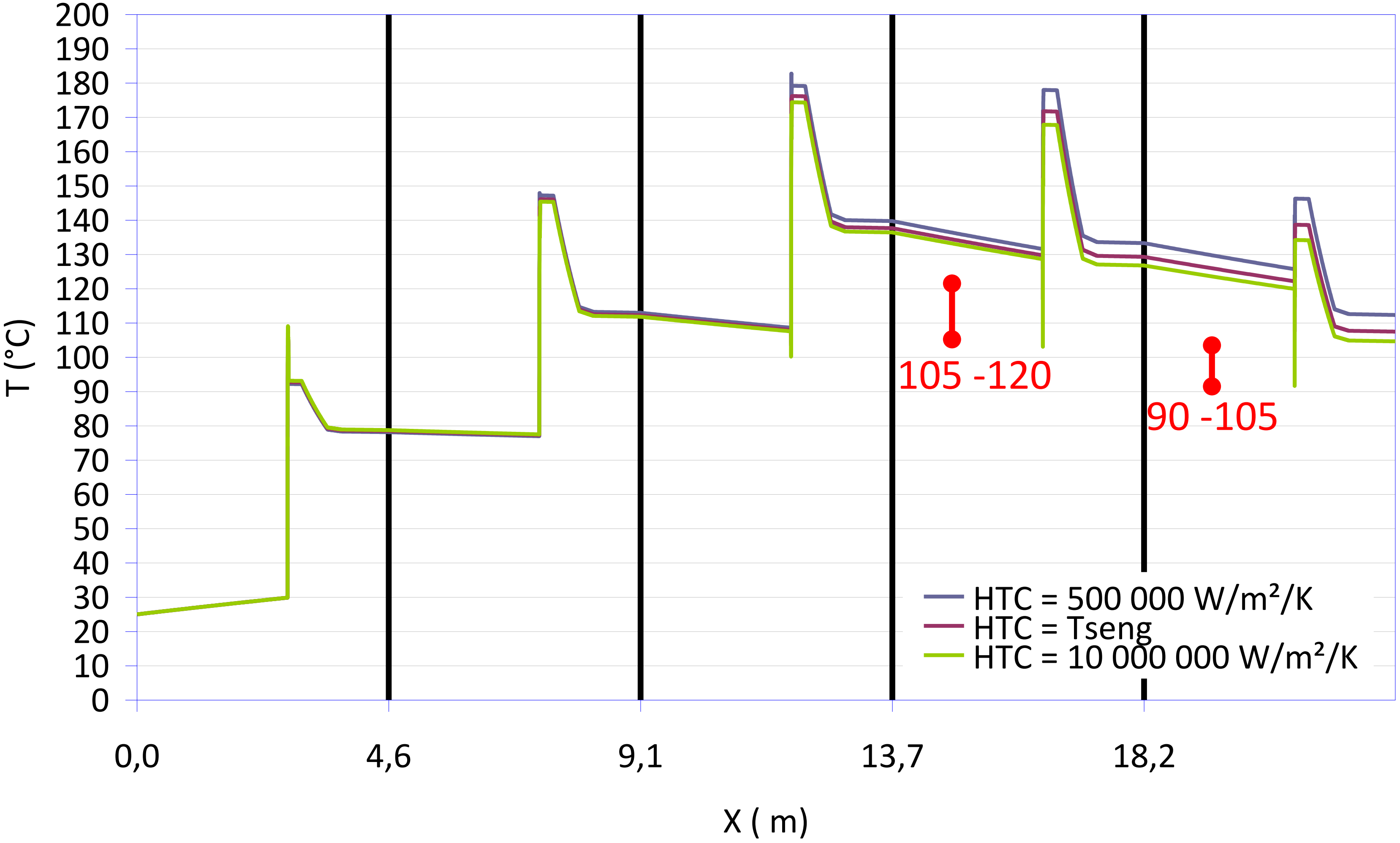
Influence of roll / strip and WR / BUR contact HTC

- An almost perfect contact : $HTC_{contact} = 10^7$ *W/m²/K*
- A weak thermal contact : $HTC_{contact} = 5.10^5$ *W/m²/K*
- $HTC_{contact} = 3800 \cdot \frac{2\lambda_{Roll}\lambda_{Strip}}{\lambda_{Roll}+\lambda_{Strip}} \cdot R_q^{-0.257} \left[\frac{P}{P+3.\sigma_0}\right]^{0.94} + \left(\frac{\lambda_{Lub}}{h}\right)(1-A)$ (A.A. Tseng)

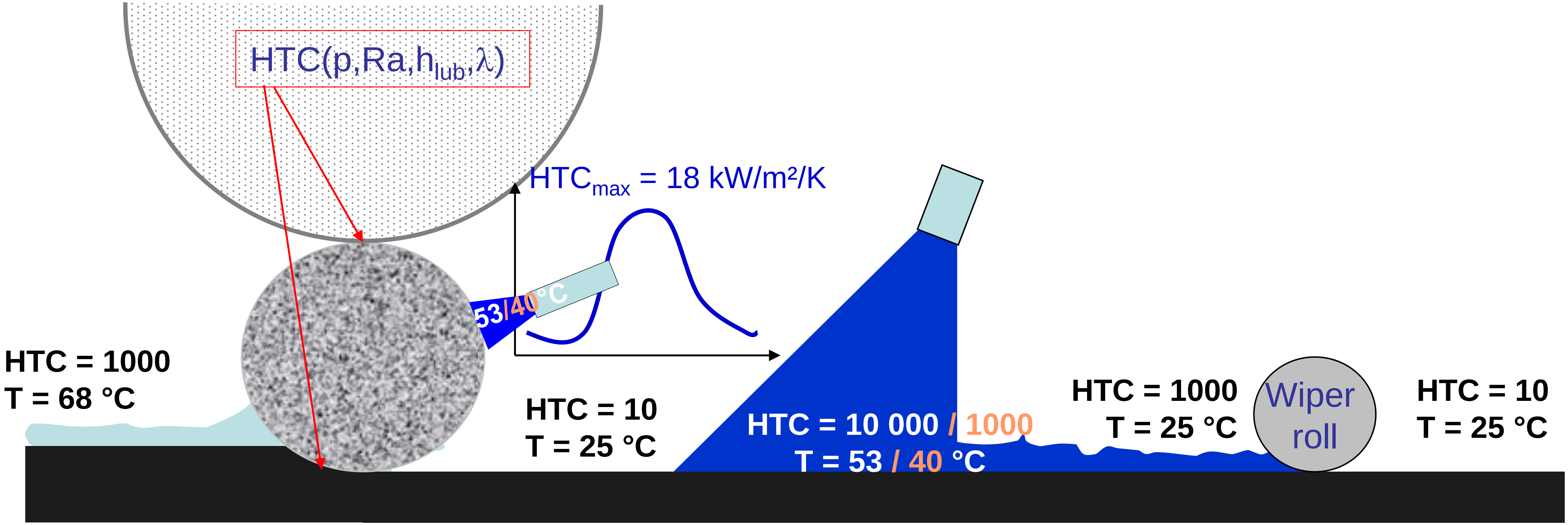


Quite low impact :

high speed

very short contact times

Influence of roll / strip coolant temperature and HTC



$HTC(p, Ra, h_{lub}, \lambda)$

HTC_{max} = 18 kW/m²/K

53/40°C

HTC = 1000
T = 68 °C

HTC = 10
T = 25 °C

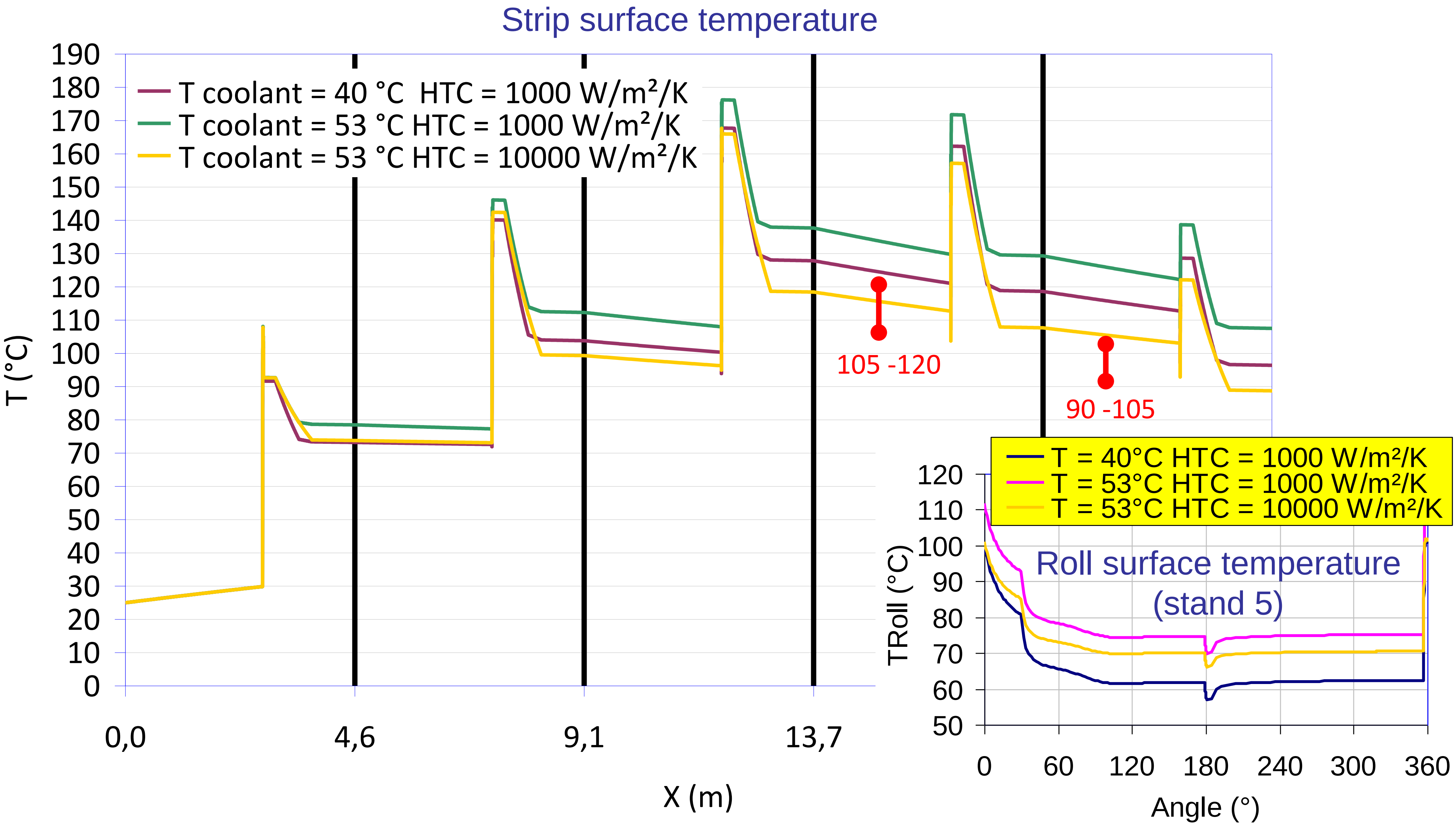
HTC = 10 000 / 1000
T = 53 / 40 °C

HTC = 1000
T = 25 °C

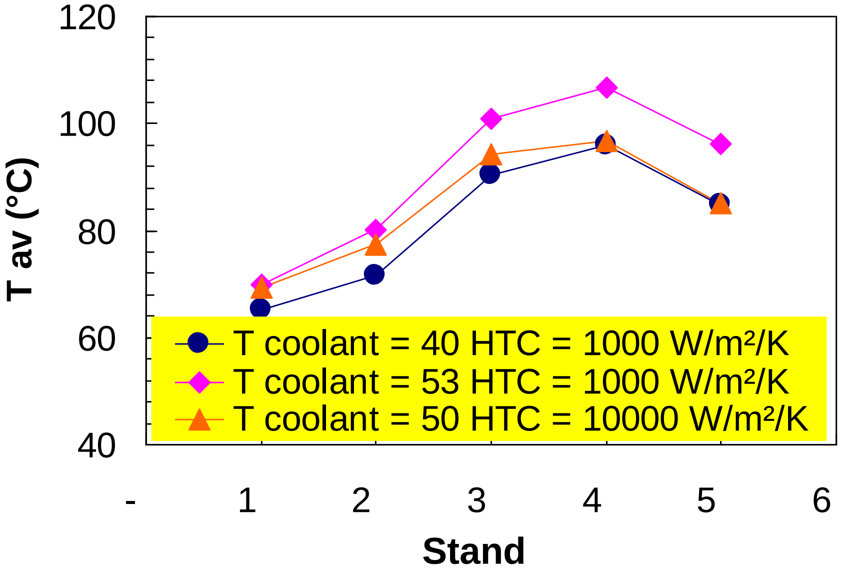
Wiper roll

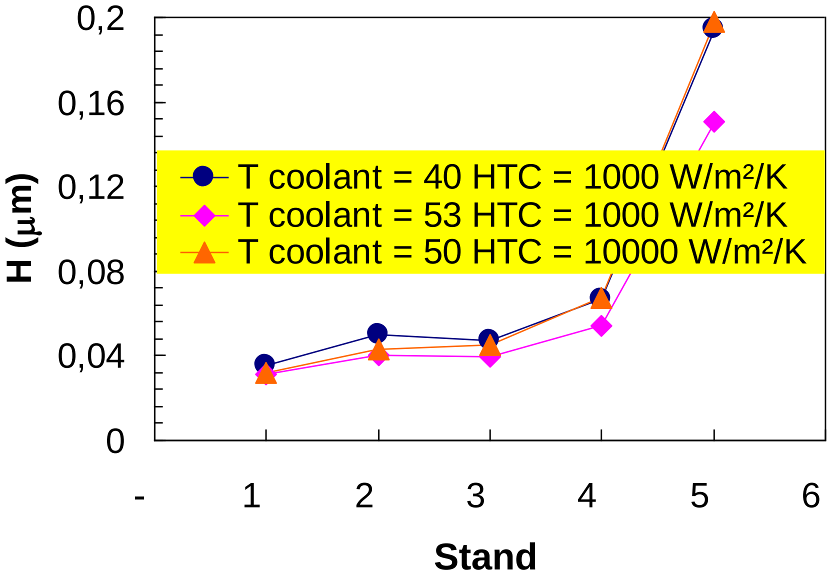
HTC = 10
T = 25 °C

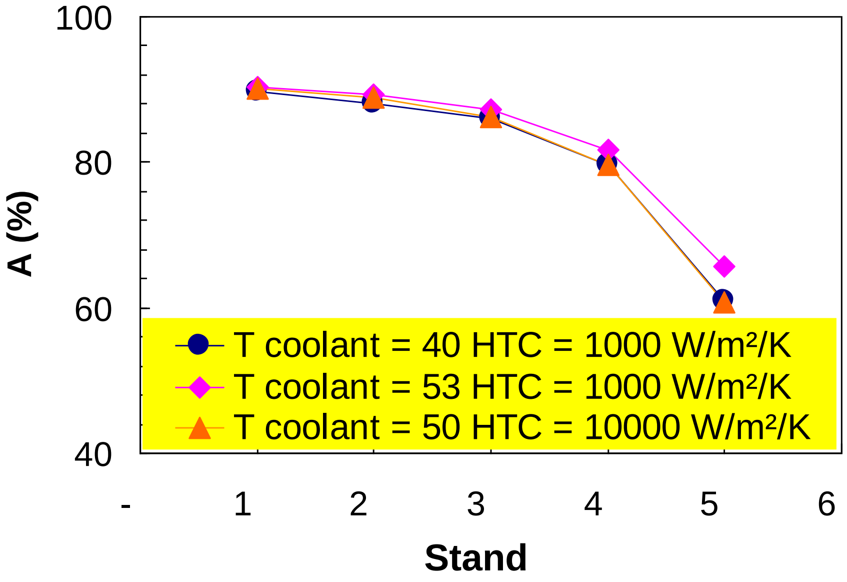
Strip and roll coolant come from the same tank → same temperature

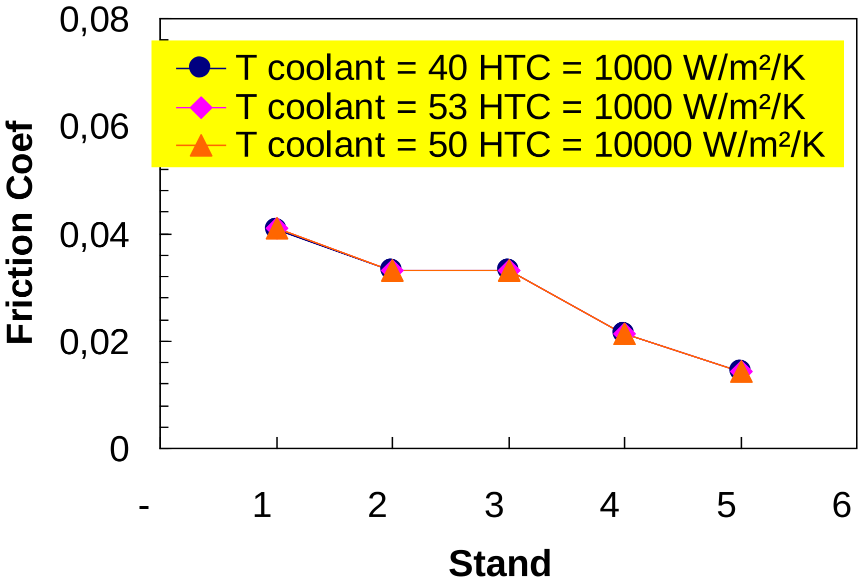


- Decreasing coolant temperature by 13°C brings the strip surface temperature down by ~ 10°C
- High efficiency strip cooling sprays as compared to poor ones has a larger effect









Entry temperature is changed by 15°C, lubricant film thickness by 25%,
yet the influence on friction remains small: *it is difficult to escape such a boundary regime*

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CONCLUSIONS & FUTURE WORK

➢ A simple thermal model allows the roll and strip surface temperatures to be computed all along a 5-stand tandem cold strip mill

➢ temperature impact on lubrication is taken care of by a simple coupling with a mixed lubrication model nested in a roll / strip deformation model

➢ therefore, the multiple couplings can be analyzed
(temperature → friction → stresses, loads … → temperature)

➢ application to the tandem mill proves various degrees of sensitivity:

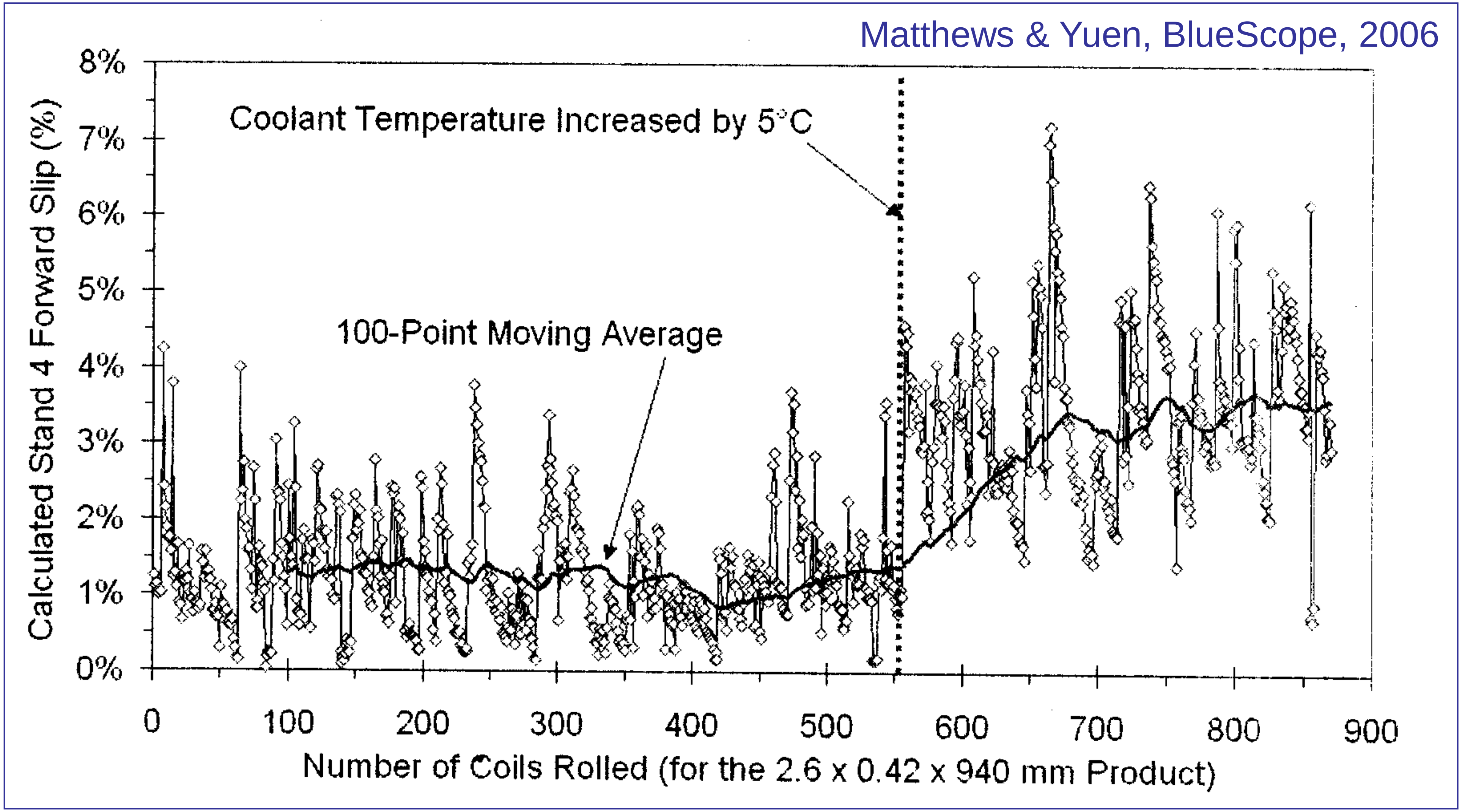
✓ little sensitivity to solid / solid heat transfer coefficient due to high speed

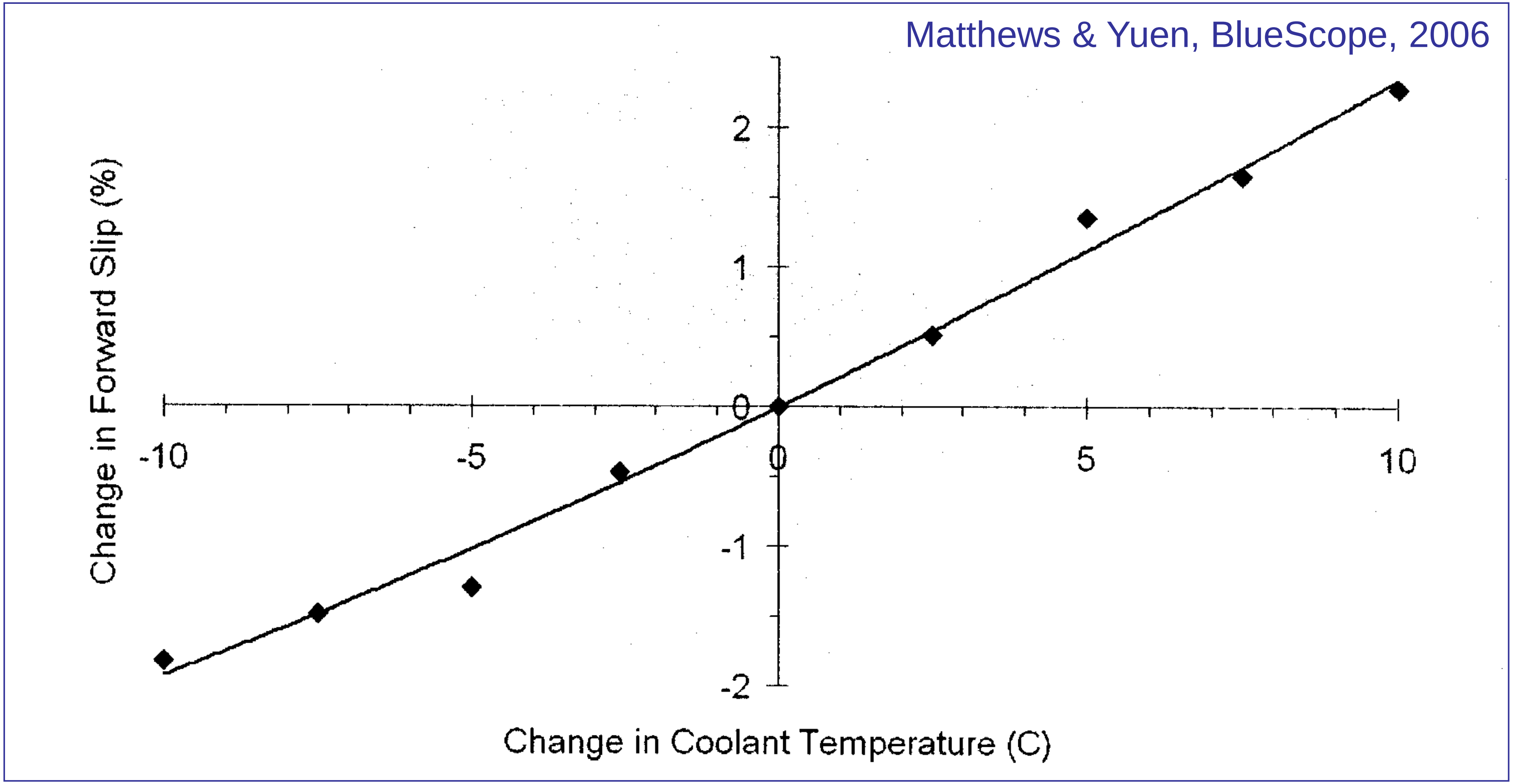
✓ roll temperature is mostly sensitive to roll cooling, strip temperature is mostly sensitive to strip cooling; *this « decoupling » is an effect of the low sensitivity to contact heat transfer*

✓ strip cooling is the most efficient thermal actuator under the presently studied conditions

✓ yet, its effect on lubrication (film thickness) is weak, its effect on friction very small

How general is this ?

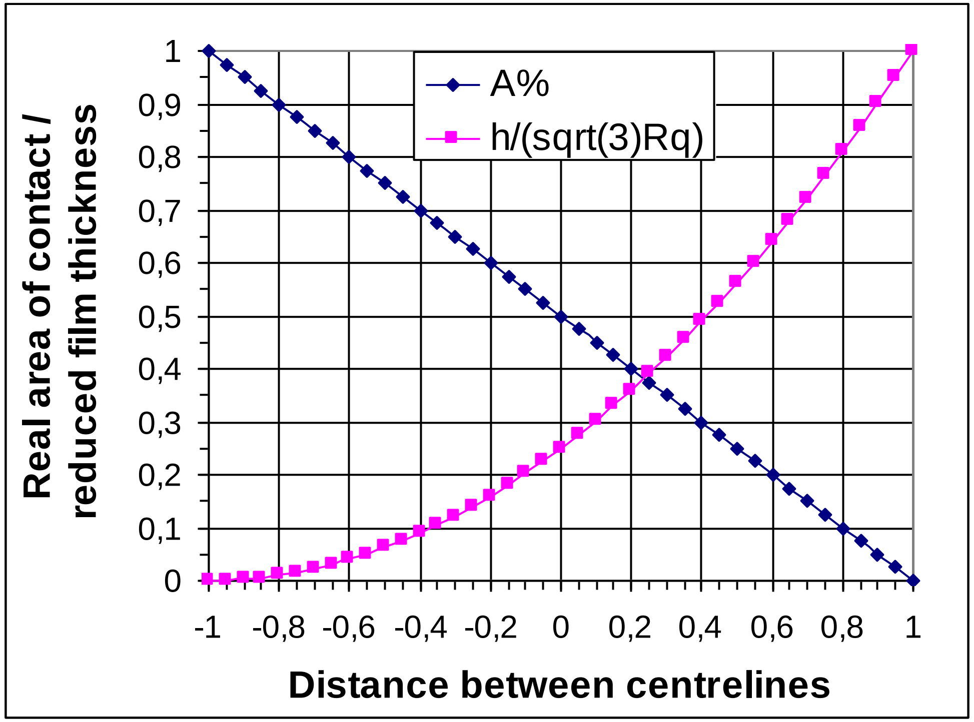

Matthews & Yuen, BlueScope, 2006

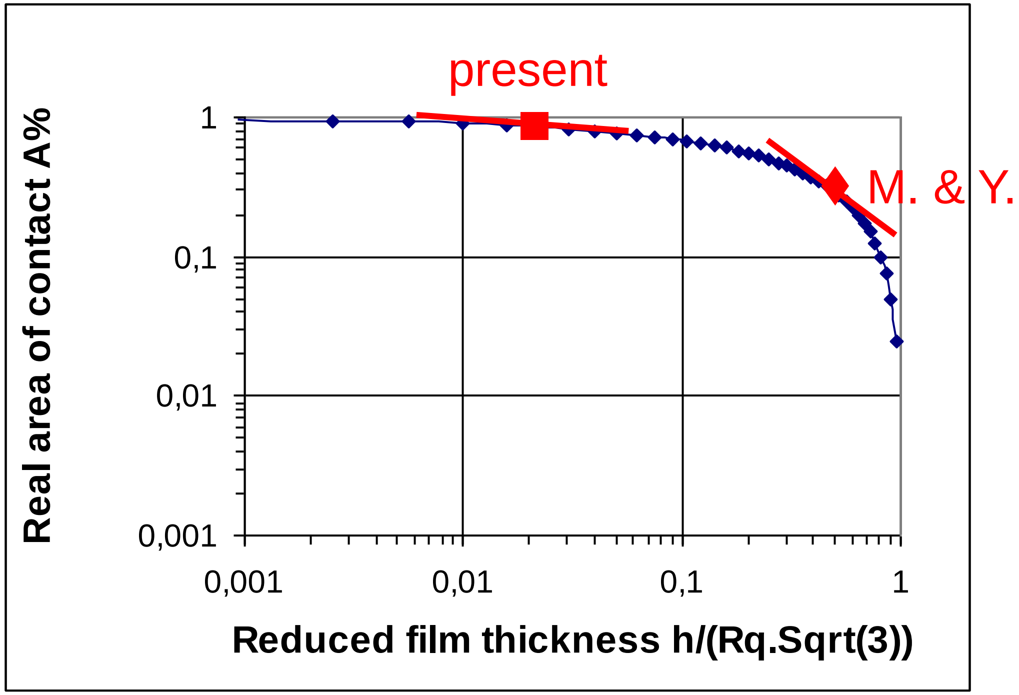

Matthews & Yuen, BlueScope, 2006

Future work on evaluation of which cases are most cooling – sensitive.

$$\frac{\Delta\mu}{\mu} \propto \frac{\Delta A}{A} \propto \left(\frac{\partial LnA}{\partial Lnh}\right)\frac{\Delta h}{h} \propto \left(\frac{\partial LnA}{\partial Lnh}\right).\frac{\Delta\eta}{\eta} \approx \left(\frac{\partial LnA}{\partial Lnh}\right).\left(\frac{\partial\left(Ln\eta\right)}{\partial T}\right).\Delta T \approx \left(\frac{\partial LnA}{\partial Lnh}\right).\frac{Q_{arrh}}{RT^{2}}.\Delta T$$

Case of longitudinal saw-tooth roughness





Thanks for attention