WP3.1.4: *FEA of TMC ATLLAS generic leading edge model wing*

Numerical modelling of TMC ATLLAS generic leading edge model wing: discovered problems and technical solutions

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ATLLAS²
Aero-Thermodynamic Loads on Lightweight Advanced Structures II

SEVENTH FRAMEWORK PROGRAMME

esa ALTA EADS FOI ITLR

DLR MBDA MISSILE SYSTEMS STARCS Aerodynamics Research & Development Member of the Sjöland&Thyselius Group UNIVERSITE PIERRE & MARIE CURIE LA SCIENCE A PARIS

CANARD Model

- FEA of TMC ATLLAS generic leading edge model wing – CANARD is designed and provided by TISICS (calculation using **ANSYS©)**

Outer shell
(Ti6242)
$\delta < 0.2$ mm → not considered

TMC
(60% Ti6242 + 40% SiC,
fibre orientation parallel to X-axis)

Cooling Core
(Ti6242 or Steel EN3B)

CANARD
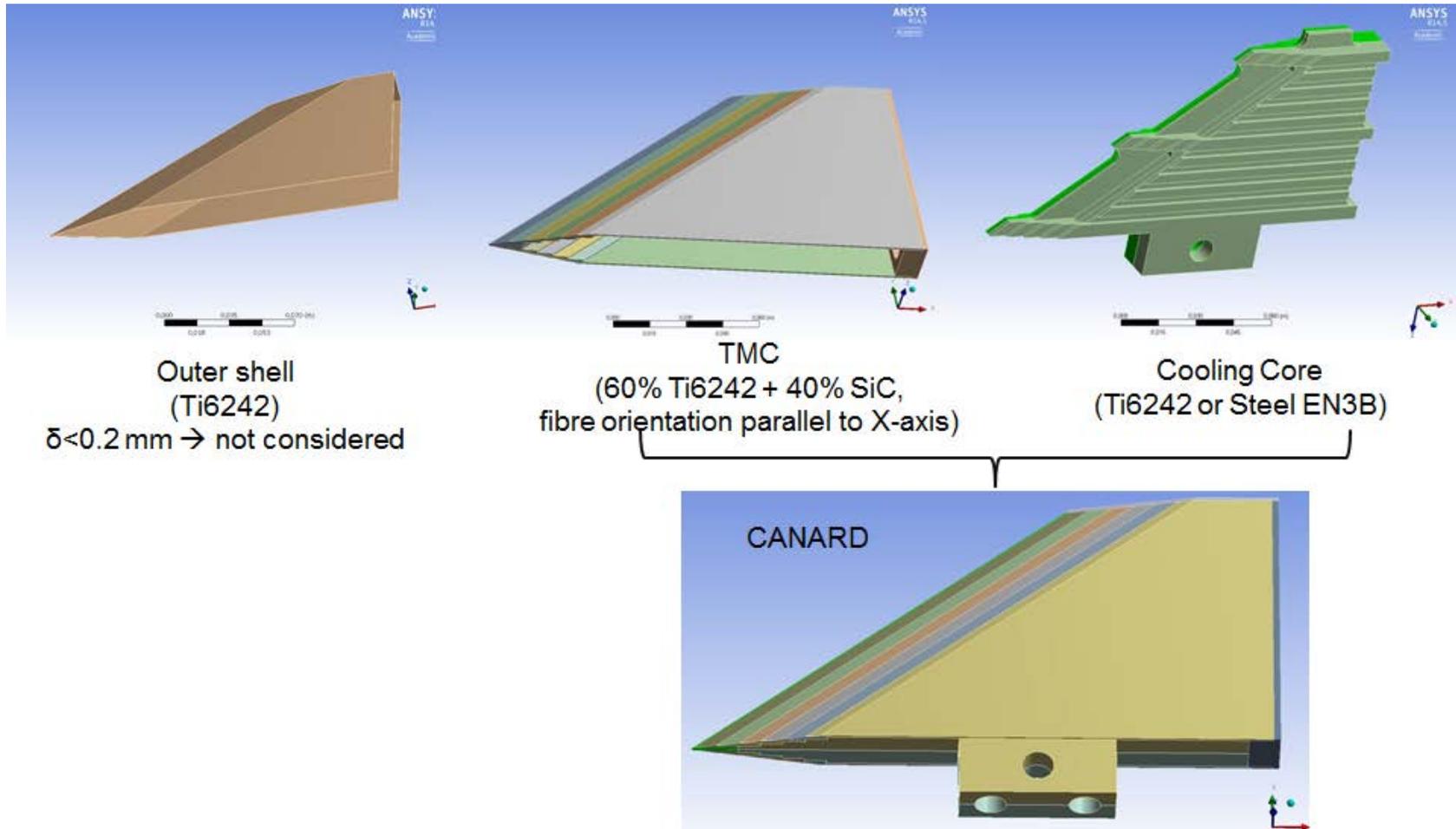
Heat flux distribution over the TMC layers
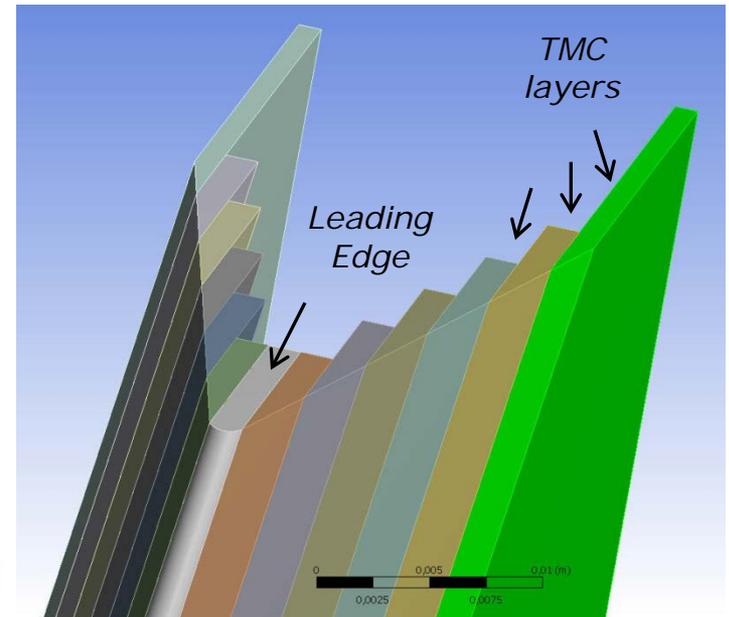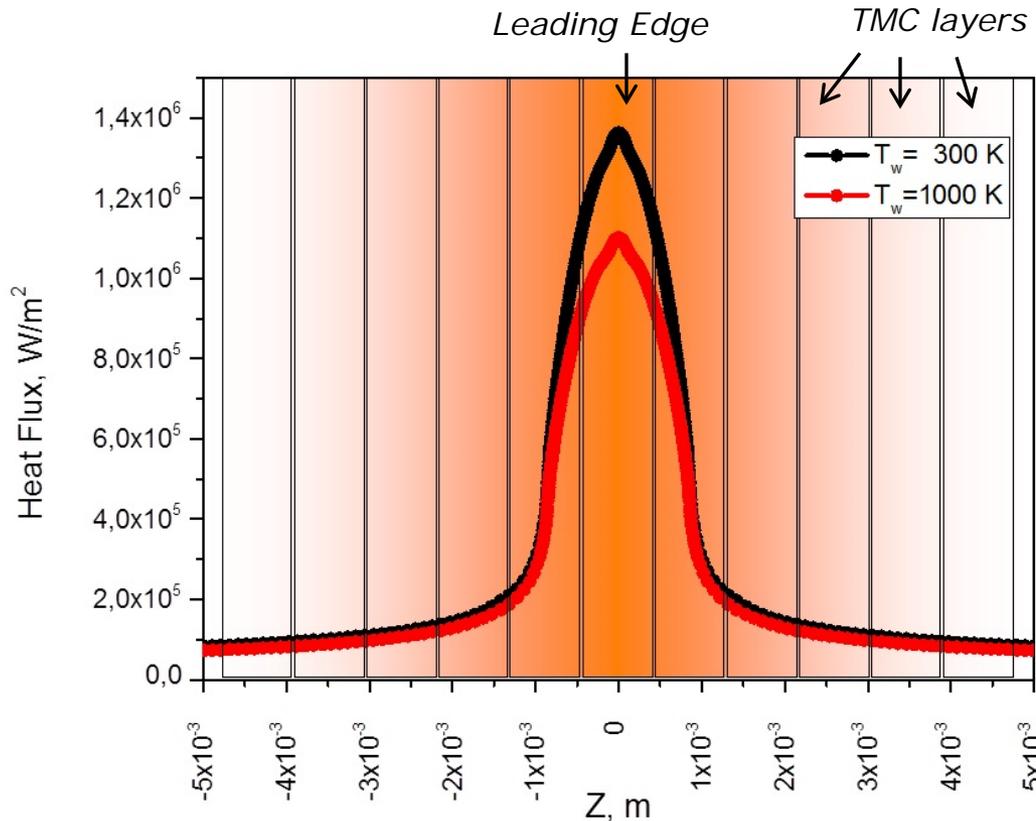
Testing in L3K DLR´s arc heated facility: calculation by Dr. B. Esser (DLR) for for the radiused leading edge of 0.8 mm for the two constant wall temperatures of 300 K and 1000 K
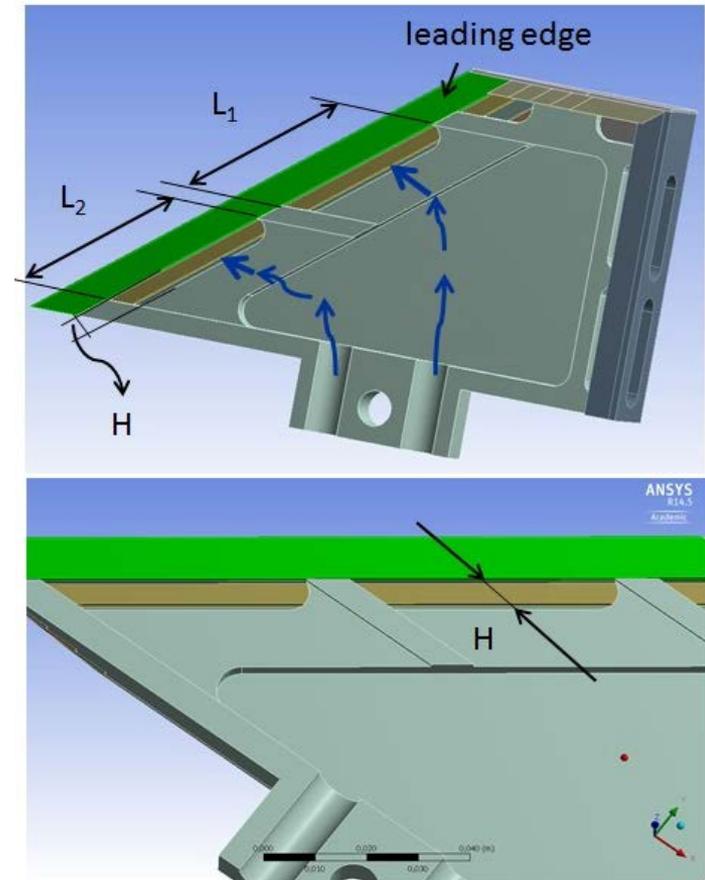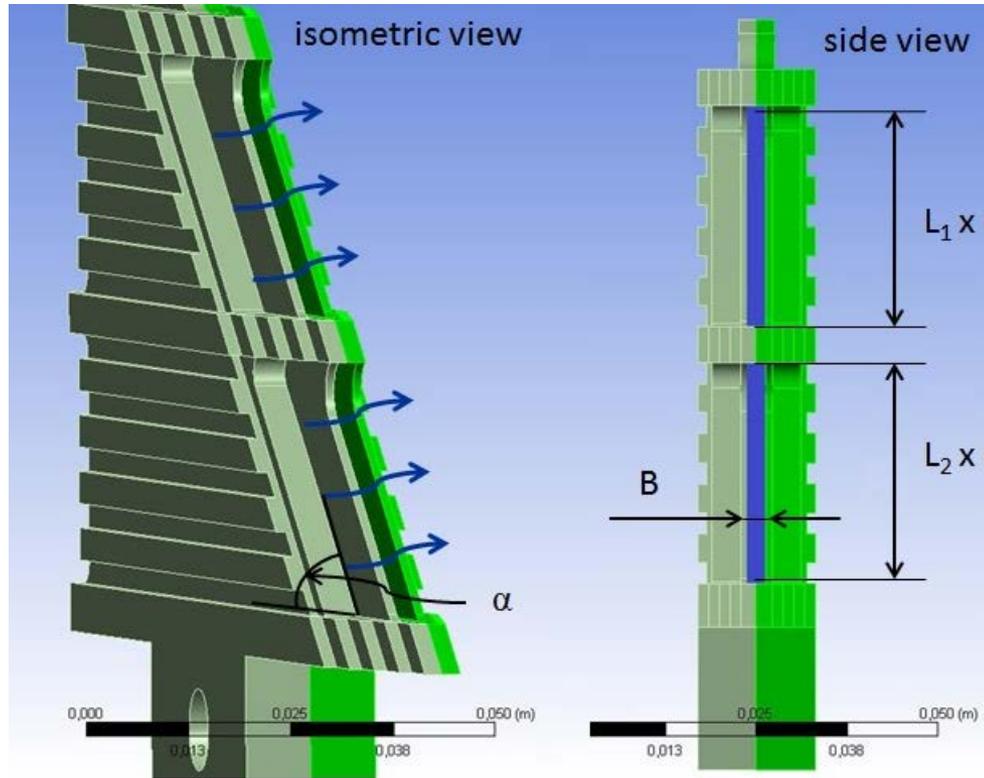
Slot jet (blue area) with the following geometric parameters:

B = 5 mm – width of slots;

$L_1 = L_2$ = 50 mm - length of slots

Heat transfer coefficients calculation - s. in Annex 1

inner surfaces of the TMC layers

Air inlet mass flow: 25 g/s

inner cavities

hollow space Inside the cooling core

internal channels between the ribs on the cooling core (10 channels on each side)
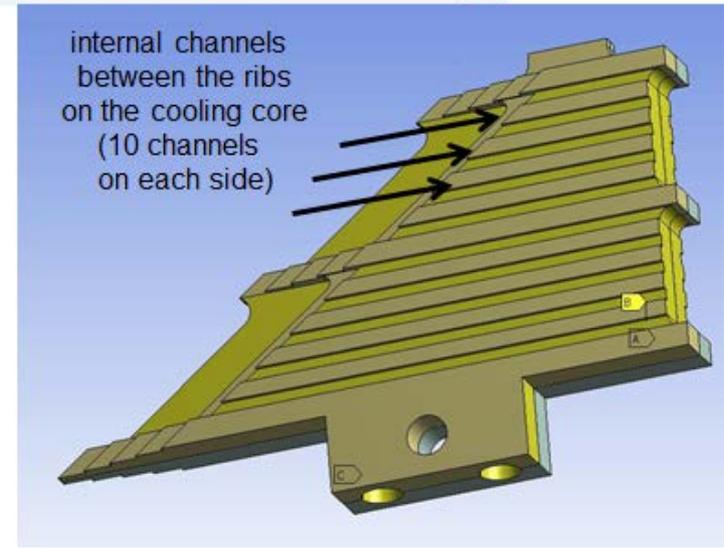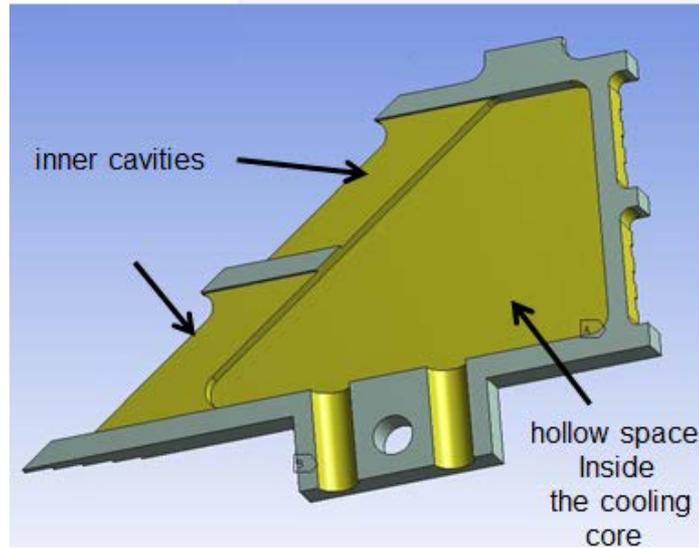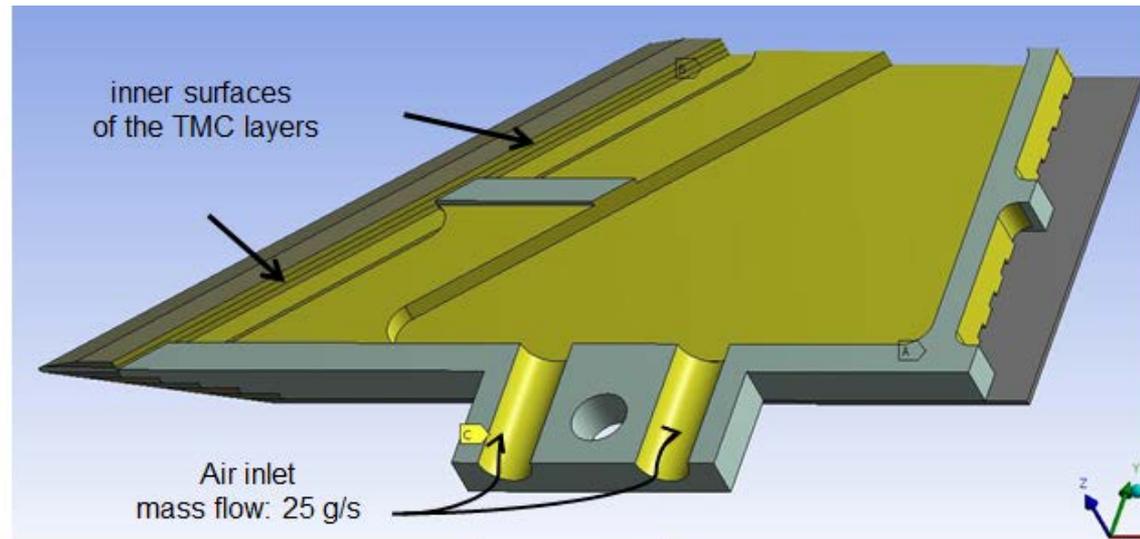
Cooled surfaces are marked in yellow

Heat transfer coefficients calculation - s. in Annex 2

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cooled foot
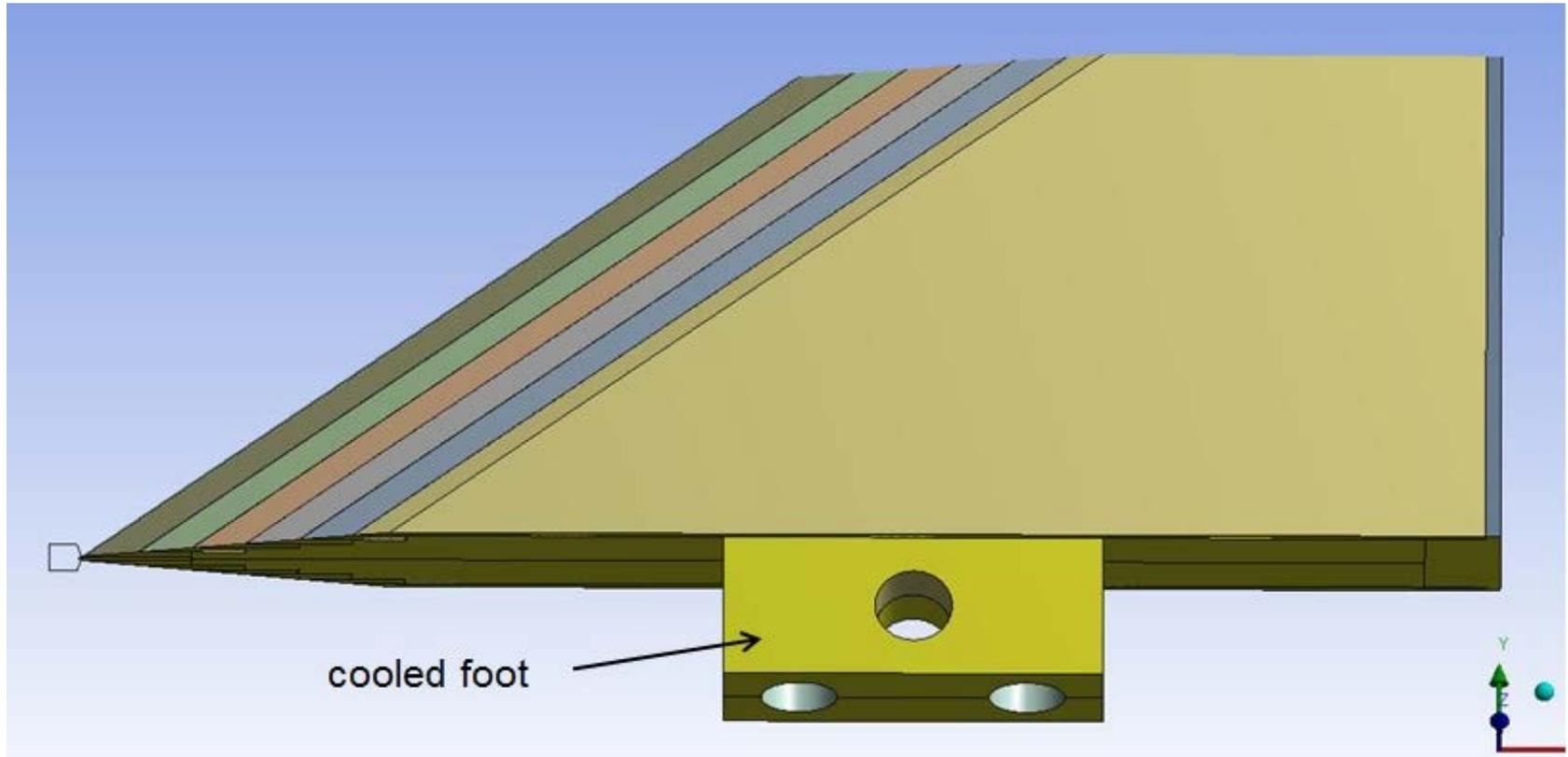
Leading edge temperature

- air mass flow: 25 g/s
- maximum heat flow: $1.02e+6$ W/m^2
- cooling core: steel EN3B

$T_{max} \sim 2000$ °C
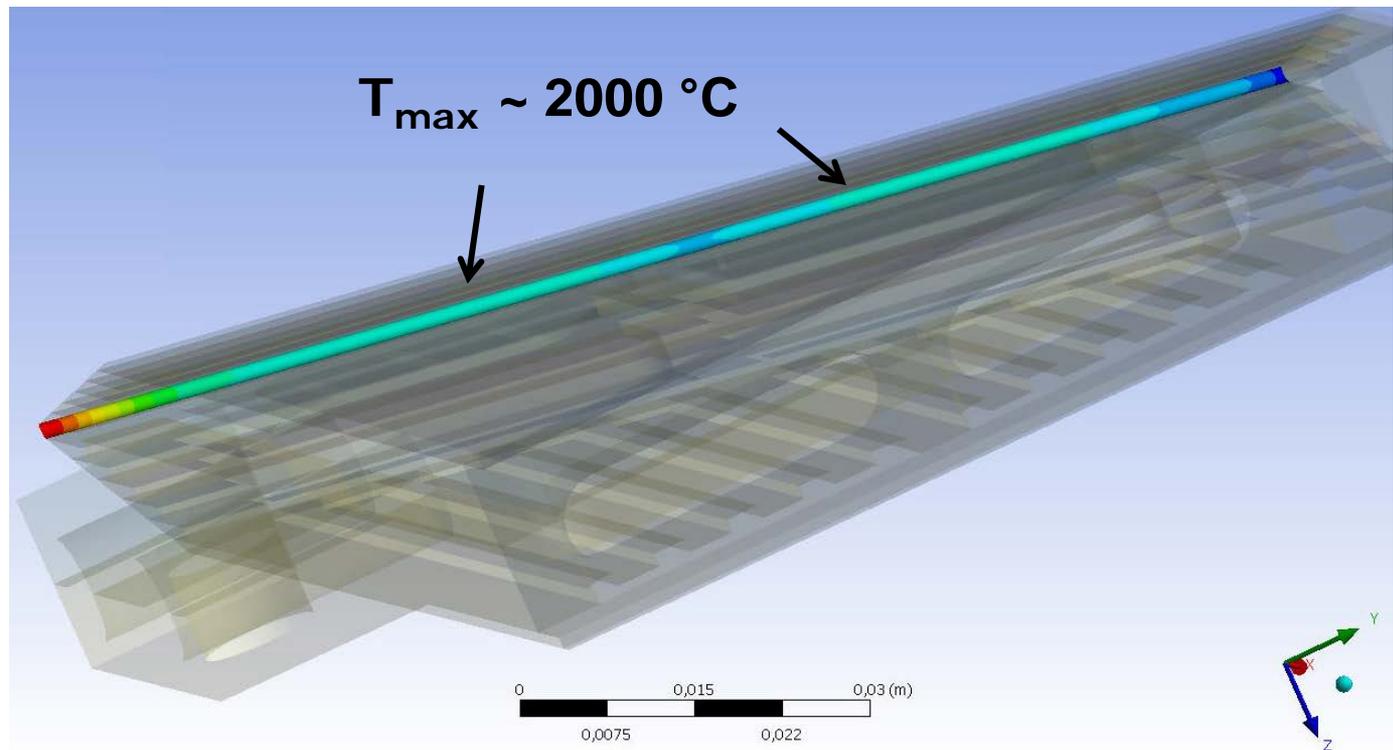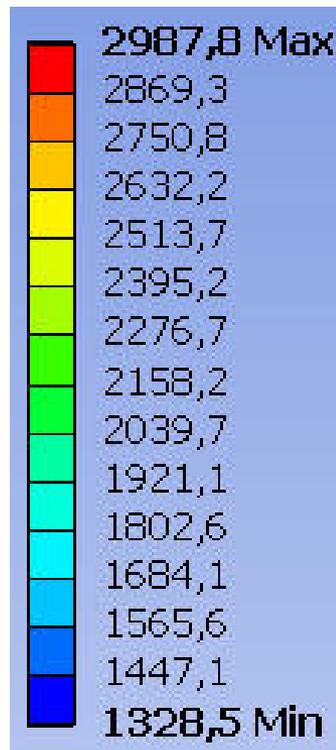
Note: Operational limits of TMC´s material exceed significantly

CANARD Model (I) does not provide adequate cooling

CANARD Model (I)
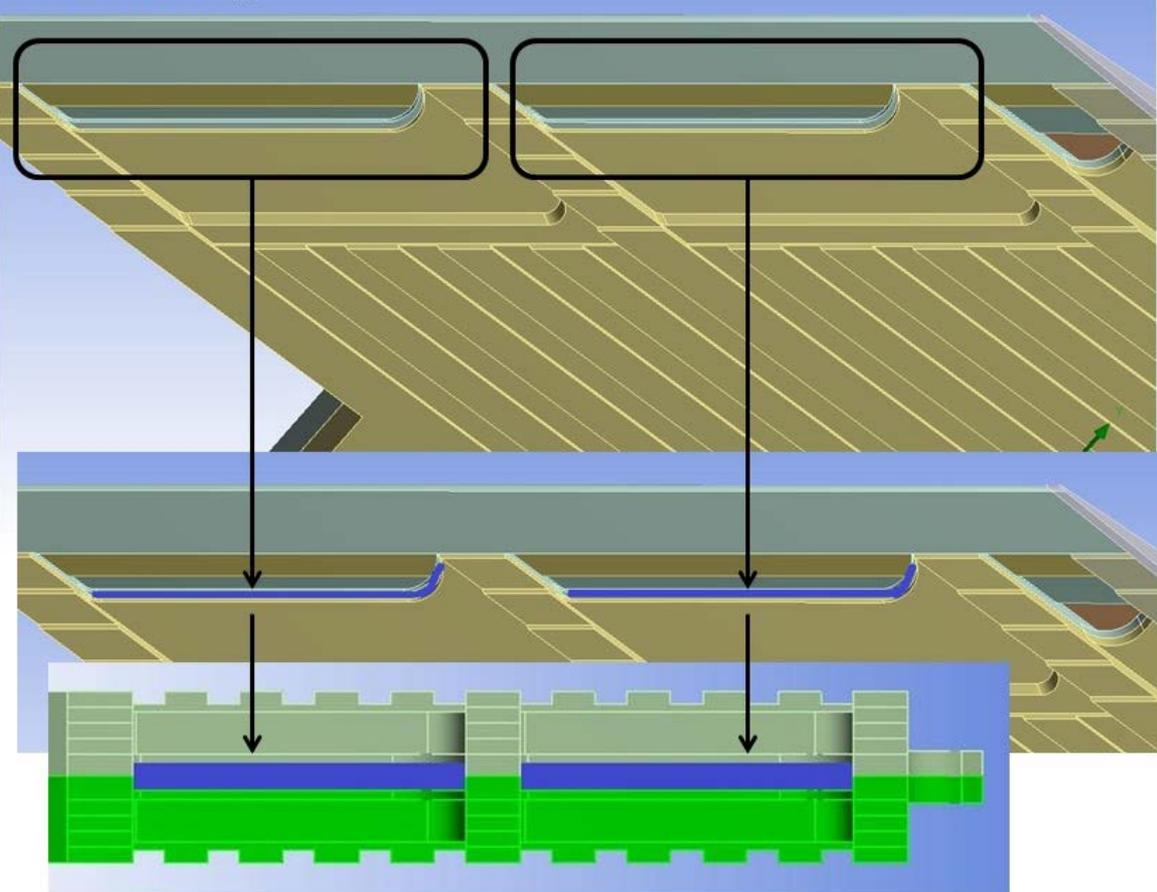
The occurring slot velocities for impingement cooling were detected to be too low which effects in low heat transfer coefficients and hence cooling efficiency

The size of the cooling slots (blue areas) and mainly its width must be significantly reduced in terms of increasing the air flow rate

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Variations of slit nozzle:

CANARD Model (I)

CANARD Model (II)

selected option
↓
further optimization to **B=0,5 mm**
↓
doubled increase of impingment cooling: $h_{avg} \approx 3000\ W/(m^2K)$
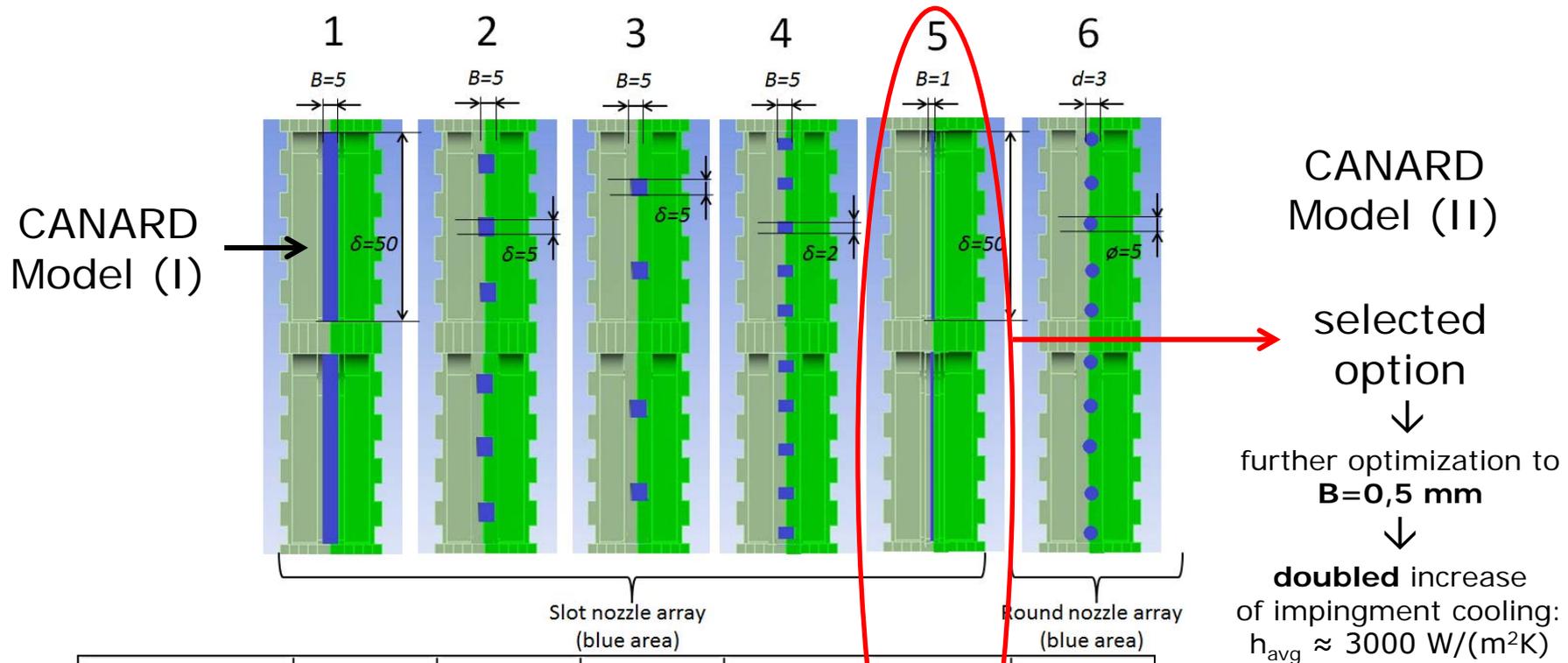
	1	2	3	4	5	6
impingement	1	2	3	4	5	6
h_{avg}, $W/(m^2K)$	148	783	1053	1500	1525	1120

10 times increased

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Thin slit nozzle with B=0,5 mm

1). original length
B=0,5

$\delta=50$

2). reduced length
B=0,5

δ_1

δ_2 $\Sigma\delta=45$

δ_3

Slot nozzle array (blue area)

Mass Airflow:

- 25 g/s - nominal
- 50 g/s - doubled

Calculated variations:

- nominal mass flow, original length
- nominal mass flow, reduced length
- doubled mass flow, original length
- doubled mass flow, reduced length

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Nominal Mass Airflow:		Doubled Mass Airflow:	
• 25 g/s (P = 1 bar, T = 20 °C)		• 50 g/s (P = 4 bar, T = 20 °C)	
Original length	Reduced length	Original length	Reduced length
$B = 0,5$ mm	$B = 0,5$ mm	$B = 0,5$ mm	$B = 0,5$ mm
$\delta = 50$ mm	$\Sigma\delta = 45$ mm	$\delta = 50$ mm	$\Sigma\delta = 45$ mm
$L = 2 \times \delta =$	$L = 2 \times \Sigma\delta =$	$L = 2 \times \delta =$	$L = 2 \times \Sigma\delta =$
$= 2 \times 50 =$	$= 2 \times 45 =$	$= 2 \times 50 =$	$= 2 \times 45 =$
$= 100$ mm	$= 90$ mm	$= 100$ mm	$= 90$ mm
$S = B \times L = 50$ mm^2	$S = B \times L = 45$ mm^2	$S = B \times L = 50$ mm^2	$S = B \times L = 45$ mm^2
Defining parameter: B	Defining parameter: B	Defining parameter: B	Defining parameter: B
$H = 6$ mm	$H = 6$ mm	$H = 6$ mm	$H = 6$ mm
Martin [1]: for arroy of slot nozzle	Martin [1]: for arroy of slot nozzle	Martin [1]: for arroy of slot nozzle	Martin [1]: for arroy of slot nozzle
$h_{avg} = \mathbf{2800}$ W/(m^{2}K)	$h_{avg} = \mathbf{3000}$ W/(m^{2}K)	$h_{avg} = \mathbf{4455}$ W/(m^{2}K)	$h_{avg} = \mathbf{4780}$ W/(m^{2}K)

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Nominal Mass Airflow: ● 25 g/s (P = 1 bar, T = 20 °C)		Doubled Mass Airflow: ● 50 g/s (P = 4 bar, T = 20 °C)	
Original length	Reduced length	Original length	Reduced length
Impingement: h_{avg} = **2800** W/(m^{2}K)	Impingement: h_{avg} = **3000** W/(m^{2}K)	Impingement: h_{avg} = **4455** W/(m^{2}K)	Impingement: h_{avg} = **4780** W/(m^{2}K)
Input: h_{avg} = 500 W/(m^{2}K)	Input: h_{avg} = 500 W/(m^{2}K)	Input: h_{avg} = 900 W/(m^{2}K)	Input: h_{avg} = 900 W/(m^{2}K)
Inner surfaces: 230 < h_{avg} < 1000	Inner surfaces: 230 < h_{avg} < 1000	Inner surfaces: 410 < h_{avg} < 1800	Inner surfaces: 410 < h_{avg} < 1800
Side ribs: h_{avg} = 1000 W/(m^{2}K)	Side ribs: h_{avg} = 1000 W/(m^{2}K)	Side ribs: h_{avg} = 1800 W/(m^{2}K)	Side ribs: h_{avg} = 1800 W/(m^{2}K)
Water cooling (bottom): h_{avg} = 8000 W/(m^{2}K)	Water cooling (bottom): h_{avg} = 8000 W/(m^{2}K)	Water cooling (bottom): h_{avg} = 8000 W/(m^{2}K)	Water cooling (bottom): h_{avg} = 8000 W/(m^{2}K)
Back outer part: h_{avg} = 20 W/(m^{2}K)	Back outer part: h_{avg} = 20 W/(m^{2}K)	Back outer part: h_{avg} = 20 W/(m^{2}K)	Back outer part: h_{avg} = 20 W/(m^{2}K)

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| N	Z, m	Heat Flux, W/m^2		h, W/(m^{2}K)		T, K		T, °C	Surfaces
		max	average	max	average	max	average	average	
1	0,0E+00	1100608,1	1024472,8	374,1	336,0	3942	4063	3790	front edge of TMC part 1 central leading edge
2	4,0E-04	948337,5	576606,9	297,8	164,5	4184	5869	5596	front edge of TMC part 2
3	1,2E-03	204876,2	166012,7	31,3	26,8	7554	7129	6855	front edge of TMC part 3
4	2,0E-03	127149,2	114901,6	22,3	21,2	6703	6396	6123	front edge of TMC part 4
5	2,8E-03	102653,9	95010,5	20,2	19,0	6089	5992	5719	front edge of TMC part 5
6	3,6E-03	87367,1	82269,3	17,8	17,5	5895	5698	5425	front edge of TMC part 6
7	4,4E-03	77171,5	74834,8	17,1	16,5	5502	5527	5254	front edge of TMC part 7
8	5,2E-03	72498,1	38585,7	15,9	15,9	5552	5552	5279	8 - side panel of TMC part 7, parallel to the heat flow

Used in calculation as convective flow

Testing in L3K DLR´s arc heated facility:
calculation by Dr. B. Esser (DLR) for the radiused leading edge
of 0.8 mm for the two constant wall temperatures of 1000 K

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Temperature distribution on the leading edge:
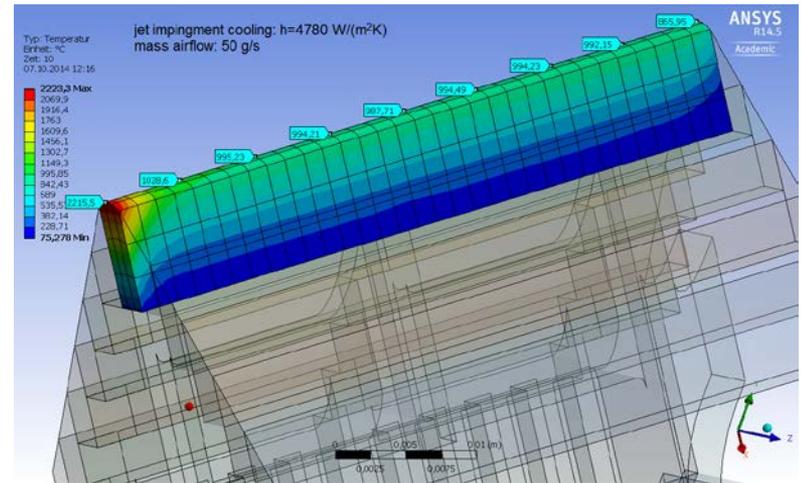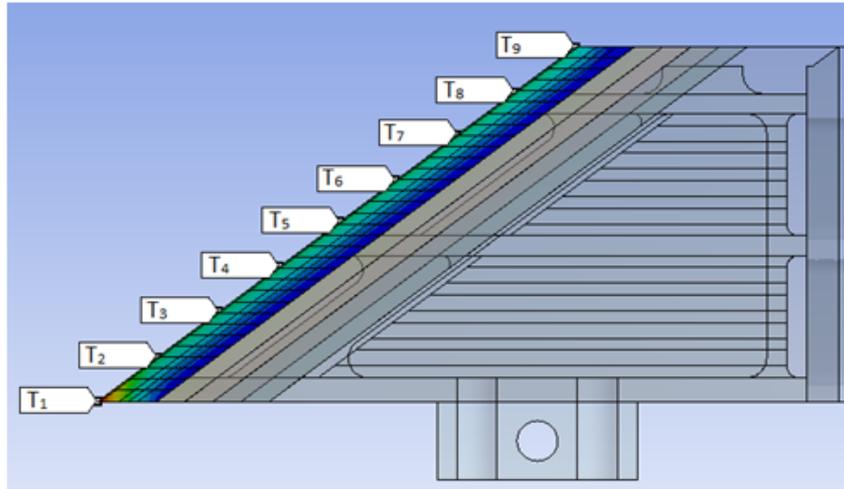
T, °C	25 g/s		50 g/s	
	h=2800 W/(m^{2}K)	h=3000 W/(m^{2}K)	h=4455 W/(m^{2}K)	h=4780 W/(m^{2}K)
T_1	2303,9	2292,9	2226,5	2215,5
T_2	1104,8	1093,4	1033,2	1028,6
T_3	1068,1	1056,8	1003,9	995,23
T_4	1065,5	1056,7	1003,1	994,21
T_5	1055,3	1046,3	995,88	987,71
T_6	1065,9	1053,8	1001,7	994,49
T_7	1066,1	1056,6	1002,4	994,23
T_8	1060,1	1050,7	999,62	992,15
T_9	945,27	919,18	872,84	865,95

$T_{max} < 1000\ °C$

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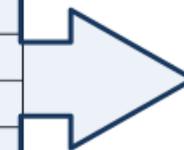
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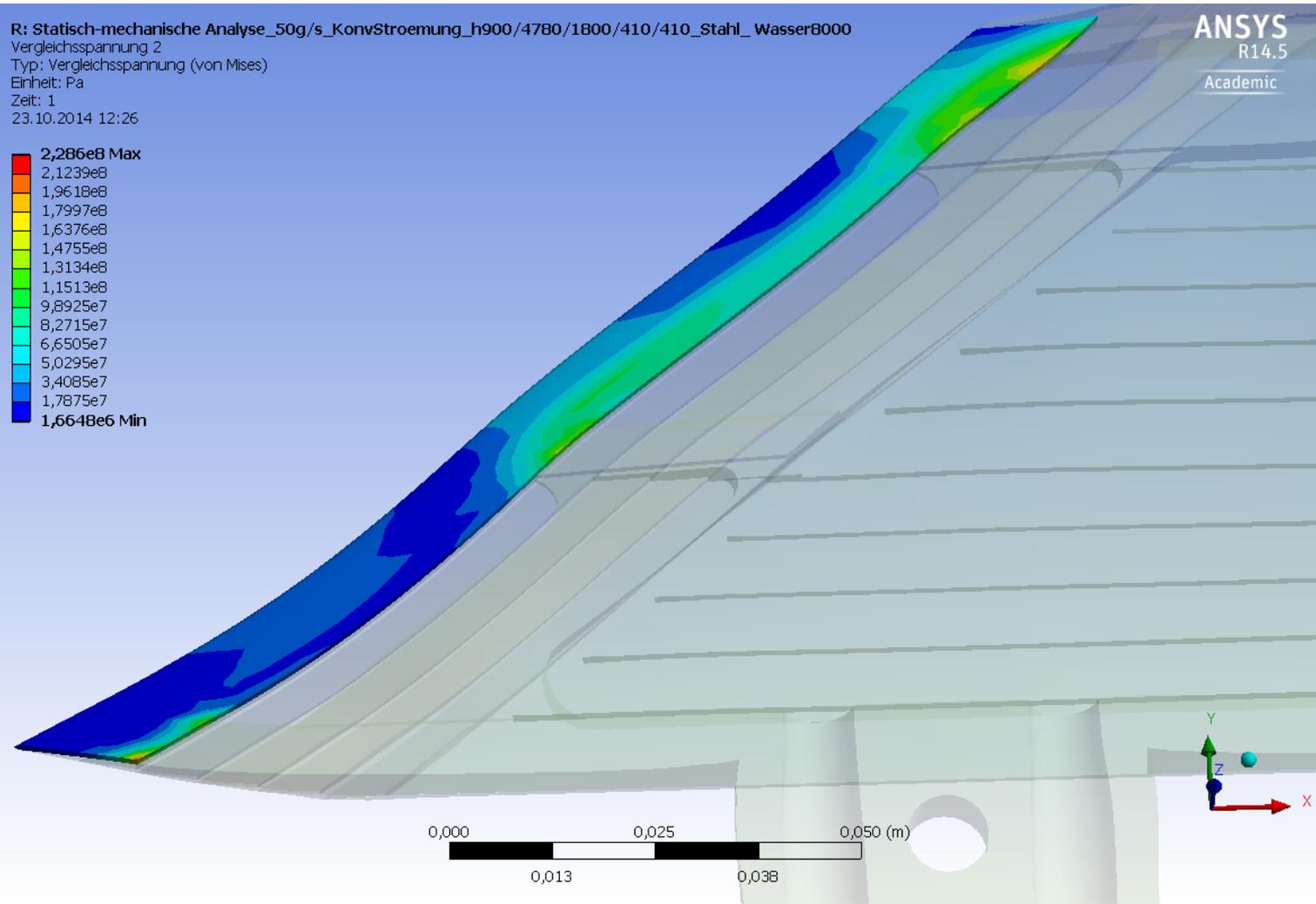
Task 3.1: Progress

- State:

  - Canard geometry and heat boundary conditions were set according to the data of the partners (TISICS, L3K DLR´s arc heated facility team)

  - Model for the canard (CANARD Model (I)) has been set up

  - Numerical simulation indicated the high temperature levels which exceed the material's (titanium and TMCs) operational limits

  - Occurring slot velocities for impingement cooling were detected to be too low which effects in low heat transfer coefficients and hence cooling efficiency

  - Multiple options of the nozzle geometry were calculated in order to increase the impingement heat transfer coefficient

  - Primary variations allowed to increase the impingement coefficient up to ten times: from 148 up to 1500 $W/(m^2K)$

  - As optimized option the cooling core geometrie with a thin slit nozzle was chosen. Further reduction in width of 0,5 mm led to almost double increase of cooling: 2800 $W/(m^2K)$

  - Further variations (CANARD Model (II) were conducted for the original and reduced slot lengths and for the nominal and doubled air mass flows of 25 and 50 g/s.

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- **D3.1.4 Results of "FEA of TMC ATLLAS generic leading edge model wing"**

    – The maximum impingment cooling was achieved for the case with the reduced slot width of 0,5 mm and reduced slot length of ca 45 mm at the doubled air mass flow of 50 g/s: h_{avg}=4780 W/(m^{2}K)

    – The maximum temperature of the leading TMC edge at the doubled air mass flow does not exceed of 1000 °C

    – The high temperature peaks at the bottom part of the leading edges of ~ 2200 °C were by numerical simulation obtained. Dr. Burkhard Esser suggests that it can be attributed to an artificial numerical effect based on a 2D external heat load as boundary conditions. Based on the results from Atllas-1, he does not expect significant increase in temperature

[1]. Martin, H. (1977). Heat and mass transfer between impinging gas jets and solid surfaces. Adv. Heat Transfer 13, 1–60.

Arroy of Slot Nozzle

Range of validity: $1500 < Re < 40000$, $0.008 \leq f \leq 2.5\, f_0$, and $1 \leq H/S \leq 40$

Average Nusselt number Nu_{avg}:

$$Nu_{avg} = Pr^{0.42} \times 2/3\, (f_0)^{3/4}\, (2 \times Re_B/\, (f/f_{0} + f_0/f\,))^{2/3}$$

$$f_0 = [60 + 4(H/S - 2)^2]^{-1/2}$$

where   S - twice slot width = nozzle hydraulic diameter
             f - relative nozzle area

Equations are for a developed jet.

[2]. Incropera, F., DeWitt, D.: Fundamentals of Heat and Mass Transfer, 2nd ed., Wiley &Sons, New York 1985

Force Turbulent Convection

Range of validity: $0.7 > Pr < 120$; $10000 < Re < 160000$; $L/D > 10$,

Average Nusselt number Nu_{avg}:

$$Nu_{avg,\ a,D} = 0.021\ (Re_{a,D})^{0.8}\ (Pr_a)^{0.43}\ (Pr_a/Pr_w)^{0.25}\ \varepsilon_l$$

where:

$Nu_{avg,\ a,D}$	average Nusselt number: $Nu = (h\ D)/k$
$Re_{a,D}$	Reynolds Number: $Re = (D\ V\ \rho)/\mu$
$Pr_a,\ Pr_w$	Prandtl Number: $Pr = (\mu\ C_p)/k$
ε_l	correlation coefficient: $\varepsilon_l = 1.38\ (L/D)^{-0.12}$

D	characteristic length parameter (e.g. diameter for flow through a pipe or around a circular cylinder at $L/D > 10$, where L is length of pipe), m
k	thermal conductivity of the fluid, W(m K)
V	characteristic velocity (e.g. average velocity for flow through a pipe or tube, m/s
ρ	density of the fluid, kg/m³
μ	viscosity of the fluid, (Pa s)
C_p	heat capacity of the fluid, (J/(kg K)

Index "a" denotes air as cooling fluid. All properties were taken for the air at the input temperature of 20 °C at 1 bar (s. Tab. 1) or at 4 bat (s. Tab. 2)
Index "w" refers to the air properties at the wall temperature (e.g. 800 °C).

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Air properties used in the calculations:

Tab. 1: pressure = 1 bar and T=20 °C: Tab. 2: pressure = 4 bar and T=20 °C:

Tab. 1		Tab. 2	
Density, (kg/m^3)	1,189	Density, (kg/m^3)	4,771
Specific Heat Capacity, (J/(kg K))	1,0068	Specific Heat Capacity, (J/(kg K))	1,012
Thermal Conductivity, (W/(m K)	2,57E-02	Thermal Conductivity, (W/(m K)	2,58E-02
Dynamic viscosity, (Pa s)	1,82E-05	Dynamic viscosity, (Pa s)	1,83E-05
Kinetic viscosity, (m^2/s)	1,53E-05	Kinetic viscosity, (m^2/s)	3,83E-06
Prandtl number (20 °C)	0,7153	Prandtl number (20 °C)	0,716
Prandtl number (800 °C)	0,734	Prandtl number (800 °C)	0,734

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