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Transient analyses on the cooling channels of the DEMO HCPB blanket concept under accidental conditions

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Helium Cooled Pebble Bed (HCPB) blanket concept is one of the DEMO (Demonstration Power Plant) blanket concepts running for the final DEMO design selection. In this paper, transient analyses on the cooling channels of the FW are carried out by means of CFD simulations for accidental scenarios like Loss-Of-Coolant-Accident (LOCA) and Loss-Of-Flow-Accident (LOFA). ANSYS-CFX is used for the simulations. The simulation results help to understand how fast the temperature of the FW can increase and what is the time window that is available until the temperature of the structural material reaches the design limit in order to be able to define a suitable protection strategy for the system. In view of later developments of the models, the heat transfer coefficients calculated with CFD are compared with the values predicted by two widely used correlations for turbulent pipe flows.

Keywords: thermal-hydraulics, CFD, helium cooling, first wall, LOCA, LOFA

1. Introduction

Helium Cooled Pebble Bed (HCPB) blanket concept is one of the DEMO (Demonstration Power Plant) blanket concepts running for the final DEMO design selection [1]. The HCPB blanket concept foresees a First Wall (FW) facing the plasma; a set of breeder units for tritium production is located behind the FW, containing the breeding material and neutron multipliers in form of pebble beds. The FW is a U shaped structure having cooling channels in toroidal-radial direction.

The plasma facing first wall (FW) has to absorb high heat fluxes from the plasma. In order to cool the structural material to suitable temperatures (i.e. for EUROFER in the range from 350°C to 550°C), the proper supply of coolant must be guaranteed. The HCPB blanket is designed with sufficient cooling ability under normal operational conditions [2]. However, it is necessary to study the temperature evolution in the cooling channels and the associated structures under Design Basis Accidents (DBA).

In this paper, the transient analyses on the cooling channels of the FW are carried out by means of CFD simulations for accidental scenarios like Loss-Of-Coolant-Accident (LOCA) and Loss-Of-Flow-Accident (LOFA). The LOCA due to failure of in-vessel components or pipe break leads to a rapid depressurization of the primary cooling system and loss of cooling ability. The LOCA may lead to plasma disruption, damage of structural materials, chemical reactions etc. [3]. The LOFA can be caused by coast down of the circulator or clogging in the cooling channels that the cooling ability is lost as well. First wall heat-up is a major concern in this class of accident [4]. The consequences of LOFA accidents can be mild, if plasma burn is terminated within a few seconds and circulator inertia and natural coolant convection provide sufficient level of coolant flow in the primary cooling systems [2].

ANSYS-CFX V15.0 [5] is used for the simulations. The simulation results help to understand how fast the temperature of the FW can increase and what is the time frame until the design limit is reached which is important for defining protection strategy for the system.

2. Geometry and Numerical Model

The DEMO HCPB blanket is subdivided in 16 sectors, each blanket sector comprises three outboard (OB) and two inboard (IB) segments, leading to a total number of 48 OB and 32 IB segments, respectively [2]. The FW is actively cooled by the two distinct cooling systems [2]. Depending on the case studied, either a single channel or a two-channel model is adopted. The dimensions of the first wall channel are shown in Fig. 1 and it considers the geometry of an OB-blanket. The total length of the channel is about 2.9m. The channel has a round-edged rectangular cross-section, having a size of $15x10mm^2$. The thickness of the EUROFER channel wall is 25mm. A tungsten armor of 2mm in thickness is attached on the channel wall on the plasma-facing side. Due to symmetric conditions, only a half channel or two half-channels was simulated.

A constant wall heat flux of $500kW/m^2$ is applied on the plasma-facing side (channel top surface) and $60kW/m^2$ on the Breeder Unit side (channel bottom surface). The surface heat flux reduces linearly (with respect to the channel length) through the bent to a constant value of $35kW/m^2$ on the side channel section. Three dimensional volumetric nuclear heating [6] was implemented in the CFD model. The total heating power per channel is 24.4 kW, in which the surface heating accounts for about 76%.

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Helium inlet pressure is 8MPa at a temperature of 300°C. For the reference case, the inlet mass flow rate is 66.6 g/s per channel. The cases were studied using Ansys CFX V15.0. The k-ω SST model was used, which was proved suitable for the studied cases [7]. For the mesh sensitivity, two meshes having a near-wall wall distance y+ of 7 and 14, respectively, were tested; the calculations results show essentially no difference. Therefore the coarse mesh (y+=14) was used for all calculations shown in the paper.

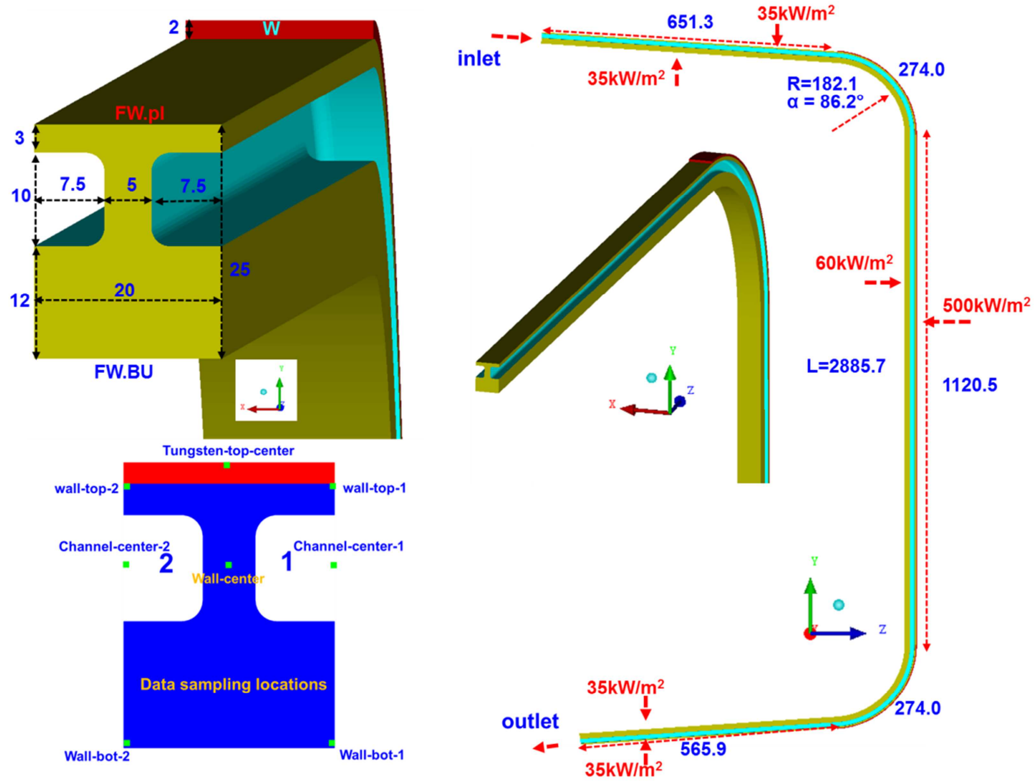

Fig.1. channel geometry.

3. Results and discussions

3.1 Effects of the surface roughness

The surface roughness data are taken from the measured values on a manufactured sample of the channel. The average roughness Ra based on several measurements is 1.55µm; the peak-to-valley roughness Rz is 9.75µm. CFX adopts equivalent sand-grain roughness, which was calculated based on Rz, using a correlation Req=0.978Rz based on literature [8]. The impact of surface roughness on the pressure loss is relatively important. Compared to the case when a hydraulic smooth surface was considered, the pressure loss increases by about 25% for the reference case (Ra=1.55µm). These simulations are in steady-state. Rougher surface improves heat transfer, therefore leads to a decrease in wall temperature as shown in Fig. 2.

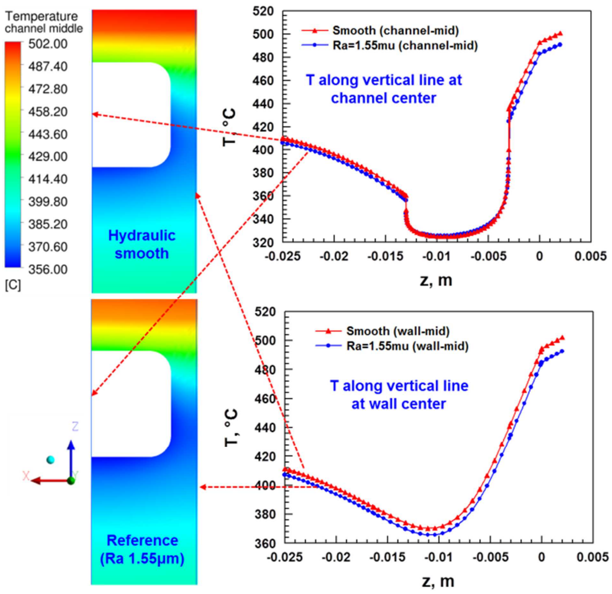

Fig.2: Comparison of wall temperature for hydraulic smooth and reference surface at channel middle.

Figure 3 shows the spatial evolution of the wall temperature along the 3 sampling lines indicated in Fig. 1 within the channel wall and inside the fluid (along the flow path, L starts at channel inlet) for the reference case. The temperature profiles correspond to 3 channel sections: side-channels where two Blanket Modules are neighboring; main channel section facing plasma and, the two bent sections (refer Fig. 1).

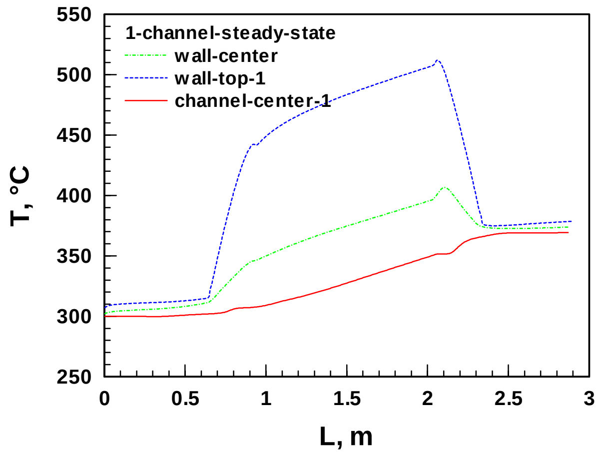

Fig. 3: Wall temperature along the channel.

3.2 Transient behaviour under accident scenarios

Table 1 lists the cases studied. Basically two accident scenarios are studied: LOFA and LOCA. The following cases have been simulated:

- One channel LOFA: this corresponds to the case when all the FW channels are cooled by the same cooling circuit with no redundancy at the level of pumping station; the mass flow rate drops to 0 and, the pressure decreased by 2 bar (corresponding to half of the pump head);
- One channel partial LOFA: this corresponds to the case when all the FW channels are cooled by the same cooling circuit but there is a redundancy at the level of the pumping stations; the mass flow rate drops to 33.3 g/s and, the pressure decreased by 2 bar;
- One channel LOCA: this corresponds to the case when all the FW channels are cooled by the same cooling circuit; the mass flow rate drops to 0 and, the pressure decreased to 1bar;
- Two channels, LOFA in one channel: this corresponds to the case when the FW channels are cooled by two distinct cooling circuits; the circuits have no redundancy at the level of the pumping station; in the channel corresponding to the circuit where the LOFA takes place the flow rate drops to 0 (no pump redundancy) and, the inlet pressure decreased by 2 bar;
- Two channels, partial LOFA in one channel: this corresponds to the case when the FW channels are cooled by two distinct cooling circuits; for the circuits there is a redundancy at the level of the pumping station; in the channel corresponding to the circuit where the LOFA takes place the flow rate drops to 33.3 g/s and, the inlet pressure decreased by 2 bar;
- Two channels, LOCA in one channel: this corresponds to the case when the FW channels are cooled by two distinct cooling circuits; in one of the circuits there is a LOCA event and the pressure drops to 1bar and the flow rate decreases to 0kg/s.

For both LOFA and LOCA cases, the mass flow rate and inlet pressure are set to decrease exponentially, at a pace $1/t^2$. The mass flow rate decreases from initially 66.6 g/s to zero as time evolves (Fig. 4), while pressure decreases by 2 bar (e.g. from 8MPa to 7.8MPa) in case of LOFA [9], and to 1 bar (decreases by 7.9 MPa) in case of LOCA (see Fig. 4). Two geometry models are used. The one-channel model is used to simulate the cases when LOCA /LOFA occur to all channels. The two-channel model is used when LOCA /LOFA occur alternatively for neighboring channels flows in same direction (co-flow). For all cases, the heating conditions remain the same as reference case (steady-state). All transient simulations use a time step of 0.5ms, corresponding to a RMS Courant number of about 3.1.

Table 1: Studied cases: prescribed mass flow rate and inlet pressure as time approaching infinity.

cases	Outlet G, g/s	Inlet P, MPa
1-ch.-LOFA	0	7.8
1-ch.-LOFA-till-half-G_ref	33.3	7.8
1-ch.-LOCA	0	0.1
2-ch.-1-LOFA	0	7.8
2-ch.-1-LOFA-till-half-G_ref	33.3	7.8
2-ch.-1-LOCA	0	0.1

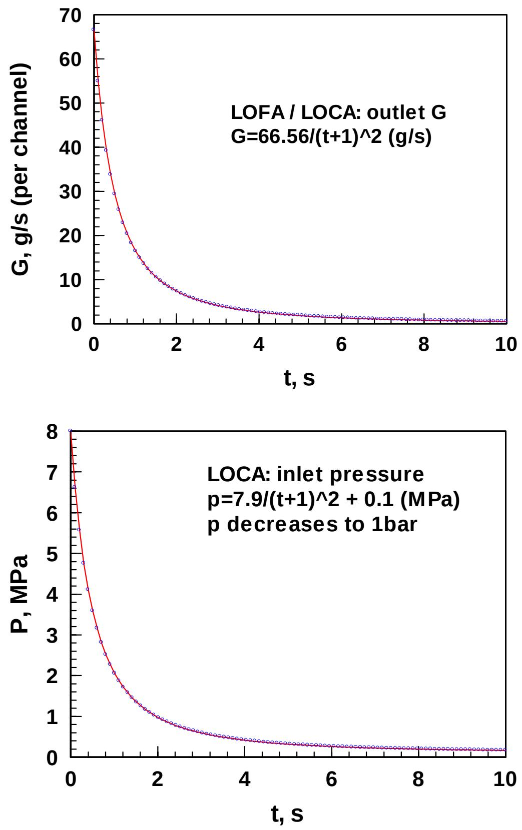

Fig. 4: Prescribed mass flow rate and inlet pressure for LOFA & LOCA.

We show here the case “two-channel-one-LOFA”. In this case, LOFA occurs to channel 1, while channel 2 operates normally. Figure 5 shows the temperature transients on the channel middle cut-plane as well as on the cut-planes 55cm upstream and downstream from the channel middle, respectively. At t=0s, the maximum temperature locates on the “tungsten-top-center”. With decreasing coolant flow rate, the temperature at “wall-top-1” becomes the highest among the sampled positions, where the temperature increases by about 100°C within 7.5 seconds (at channel middle). In contrast, the temperature at the corresponding position above the normally-operating channel “wall-top-2” increases by only 30°C within 7.5 seconds. The wall temperature increases in the flow direction due to the higher coolant temperature, roughly 0.6°C/cm.

Figure 6 shows the temperature contours on the cut-plane at channel middle.

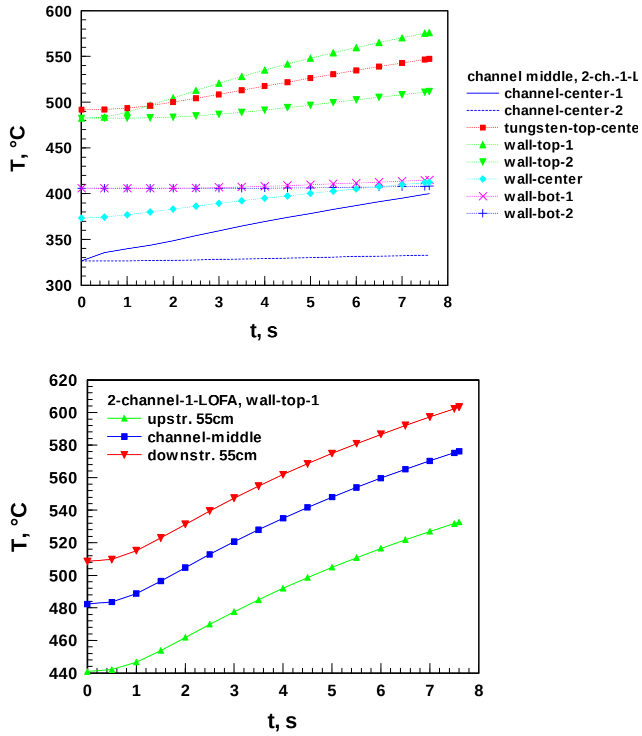

Fig. 5: temperature transients for the case “two-channel-one-LOFA”.

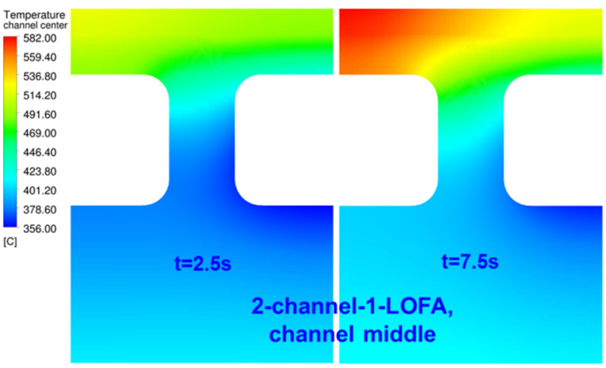

Fig. 6: temperature contours on the cut-plane at channel middle for the case “two-channel-one-LOFA”.

Figure 7 compares the fluid temperature transients at channel center (refer Fig. 1 for the locations); Figure 8 compares the wall temperature transients at two positions for all cases. All data shown in this section are for the sampling points located on a cut-plane at the middle of channel flow path. The temperature transients show little difference for both case “one-channel-LOCA” and “one-channel-LOFA”. This is because the prescribed transients of mass flow rate are the same for both cases. The inlet pressure transients show little impacts on the temperature fields. This is also true for the cases “two-channel-one-LOCA/LOFA”. Therefore, the data for all LOCA cases are not plotted in the figures.

It can be seen that the temperature rise is the fastest in case of “one-channel-LOFA”, followed by “two-channel-one-LOFA”, “one-channel-LOFA-till-half-G” and “two-channel-one-LOFA-till-half-G”.

The position “wall-top-1” represents approximately the highest wall temperature (without tungsten armor) on a given cut-plane. The temperature rise on this position is the fastest in case of “one-channel-LOFA”: rising almost linearly about 180°C within 10 seconds. For both cases “LOFA-till-half-G”, the rise in temperature is much slower, e.g. about 50°C within 10 seconds on position “wall-top-1” for the one-channel case.

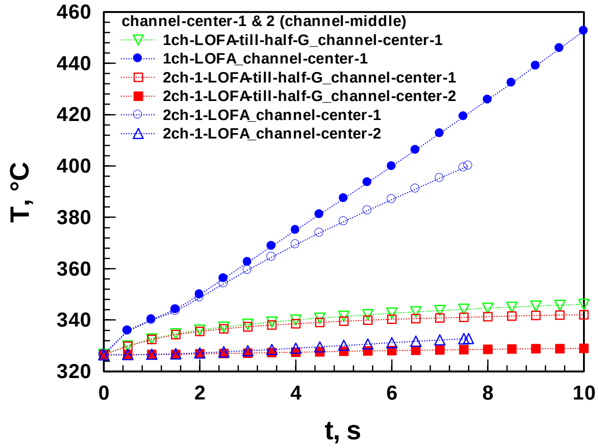

Figure 7: Comparison of fluid temperature transients on channel center for all cases.

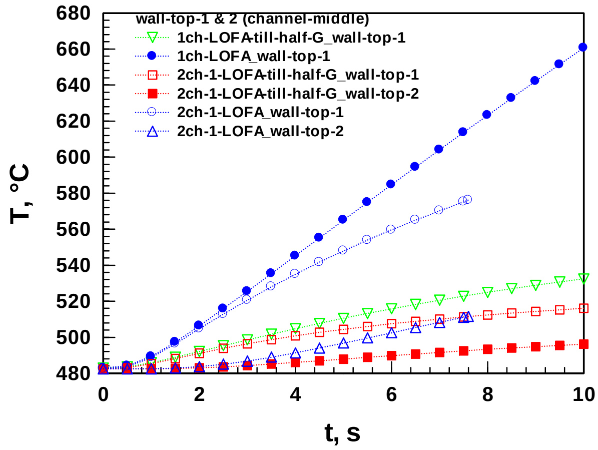

Figure 8: Comparison of wall temperature transients at four positions for all cases.

3.3 Heat transfer coefficient: comparison with correlations

The case shown here is "one-channel-LOFA". For the transient mass flow rate and inlet pressure please refer to Fig. 4.

The local friction factor at the channel middle is compared with Balsius equation ($0.3164Re^{-0.25}$) and a correlation from Gnielinski [10], shown in Figure 9:

$$f_G = (1.8log_{10}^{Re} - 1.5)^{-2} \quad (1)$$

The friction factors predicted by the two correlations are similar. The calculated friction factor is higher than predictions for Re larger than 10,000; the difference becomes larger as Re increases. Note that the correlations were developed for the smooth tubes, while the numerical case here is for a rough wall with Ra=1.55µm. The calculated friction factor for the smooth surface under steady-state condition is also shown in the figure, which shows a much lower value than the rough surface, while still higher than the predictions.

Figure 10 compares the calculated Nusselt number with the correlations. Overall, the calculation results agree quite well with the classic Dittus-Beulter correlation ($0.023Re^{0.8}Pr^{0.4}$). The Gnielinski correlation under-predicts the heat transfer coefficient for about 10% for Re larger than about 60,000. The Gnielinski correlation is given by

$$Nu_G = \frac{(f/8)RePr}{1+12.7\sqrt{f/8}(Pr^{2/3}-1)} \quad (2)$$

with f given by Eq. 1. If the calculated friction factor is used as input for the Gnielinski correlation, it tends to over-predict the Nusselt number.

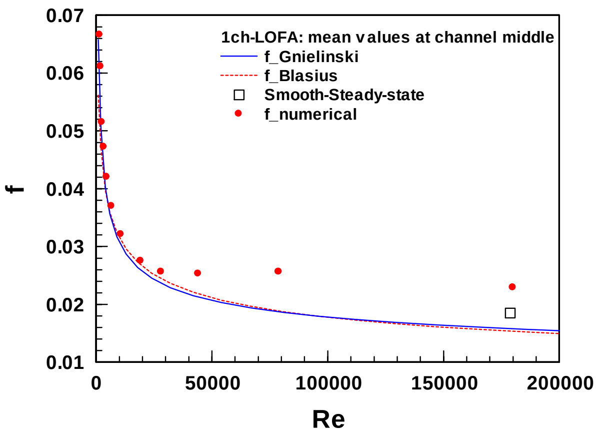

Figure 9: Local friction factor at the channel middle compared with Balsius equation and a correlation from Gnielinski [10].

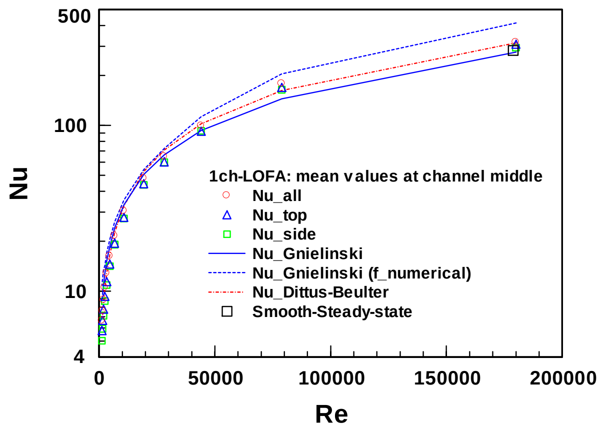

Figure 10: Comparison of calculated Nusselt number with the correlations from Dittus-Beulter and Gnielinski.

4. Summary

Transient CFD analyses on the cooling channels of the HCPB FW were carried out for accidental scenarios including Loss-Of-Coolant-Accident (LOCA) and Loss-Of-Flow-Accident (LOFA). In both cases, the wall temperature increases quickly to an unacceptable level within seconds. If the coolant flow rate is maintained at a half of nominal value in case of LOFA (partial LOFA), the wall temperature rises much slower, but will still leads to a damage of structure within minutes.

Compared with the numerical results, the friction factor predicted by Blasius correlation and Gnielinski correlation are lower. The correlations were generated for smooth surfaces, while the numerical cases are for channels with surface roughness Ra=1.5µm. The Nusselt number can be well predicted using Dittus-Boelter correlation. The Gnielinski correlation slightly under-predicts the Nusselt Number in the high Re range. The surface roughness has a big impact on pressure loss and heat transfer to a less extend.

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