Respond to reviewers comments

The authors would like to express their sincere thanks to the reviewers for the professional and thorough comments, which are quite helpful for improving the quality of the paper, as well as keeping the persistent high academic standard of International Journal of Nuclear Engineering and Design. Extensive modifications according to the reviewers' suggestions have been made. The reviewers' comments are answered one by one as below: (I have highlighted the comments in italics).

Reviewer 1:

In this study, an assessment of subchannel code COBRA-TF in addressing the effect of rod bowing on DNBR is performed. Two well known approaches for the critical heat flux (CHF) prediction are used: W3 correlation and Groeneveld look-up table. It is helpful to the safety analysis of a nuclear power plant. However, there are some shortages in the manuscript. Therefore, in the reviewer's opinion this manuscript should be recommended for publication if the following comments have been addressed.

1. *The geometry size of test section in Figure 1 should be given.*
We added the geometrical parameters of the tube bundle to the Figure 1.

2. *Please given the reason of axial power distribution in Figure 2.*
We think, one of the main reason for the power shape in Figure 2 is that it is close to the axial power shape of a real fuel assembly in a core at the beginning of a cycle. We do not explain this in the text since this axial power shape is a given boundary condition in our subchannel analysis taken from HTRF tests report [1].

3. *Measured parameters were presented in Page 5, but the calculated parameters were not given.*
All measured parameters are presented in the Appendix of the paper.

4. *The authors mentioned "from β = 0.10 the standard deviation is flattened and is independent on β. Thus the value of β = 0.10 is chosen in all further analysis"but the from β = 0.06 the standard deviation is flattened in Figure 4.*
If we take a look at Figure 4 more closely, it can be seen that after $\beta = 0.06$ standard deviation still reduces. At $\beta = 0.09$ the standard deviation rises a bit, however, after $\beta = 0.10$ the standard deviation does not change.

5. *How to measure the mass flow rate in sub-channel in Figure 11?*
In Figure 11 the calculation results of a subchannel code are presented. In HTRF tests only a total flow rate at the inlet section is provided.

6. *The authors chosen two rods CFD model rather than the test model in HTRF. Please explain.*

CFD and neutronic calculations in sections 4.4 and 4.5 mainly are for illustrative purposes. We wanted to show possible local effects which can be captured by more detailed CFD analysis, and internal rod power redistribution due to a rod shift. We believe that this topic requires more detailed analysis and deserves a separate publication. Our current work mainly devoted to the subchannel analysis of the rod bowing in a tube bundle.

7. *Indeed the present CFD physical model does not resolve the phase change at the wall where subcooled boiling is expected and no grids are inserted in the computational domain. These two important details will be factored -in in future work. Why the authors did not consider above factors?*
The reviewer is absolutely right. Indeed, the subcooled boiling regime should appear locally in the region close to the contact between the rods. Grids would increase turbulence in the flow, and improve thermal mixing after the mixing grid. However, in our illustrative calculations, we wanted to separate the effect of local heat exchange disturbance near the rod wall at the contact region from the two-phase and additional mixing effects. Effects of nucleate boiling and grids would overlap in this case, which we wanted to avoid. We added sentences about the reason for choosing this particular CFD case at the beginning of section 4.4.

Reviewer 2:

This paper deals with important and interesting topic on the effect of rod bowing on the critical heat flux. The paper covered subchannel analysis code, CFD code, and neutronics code to investigate the topic. The paper can expand our current understandings on the effect of rod bowing on the CHF. The topic and present results would be very helpful for researchers. In addition, the paper has sufficient technical quality. This paper is recommended to be published after minor revision according to the following comments.
1. *At the 8th line of page 3, the following text are unclear and needs to be more checked: "Since a significant effect of rod bowing on CHF was observed only at high pressure, bowing to contact effect only applies above a certain power threshold that increases with decreasing system pressure". Here, the word "above a certain power threshold" should be checked. Why do we have a bowing effect only above a certain power threshold? Since the CHF decreases with increasing system pressure and the bowing effect are significant at high pressure condition, then the bowing effect appears below a power threshold level.*
You are right, in this sentence, we are talking about pressure influence on the CHF in case of rod bowing. In Figure 1 a copy of Figure 4 in [9] is presented. According to this figure, the authors concluded that there is a considerable effect on DNB of a bowed rod of contacting in cold wall thimble cell at high pressures, but minimal influences on the critical power at low pressures. The sentence mentioned by the reviewer replaced by the following: "Since a significant effect of rod bowing on CHF was observed only at high pressure, bowing to contact effect only applies above a certain **pressure** threshold that increases with de-

creasing system pressure."

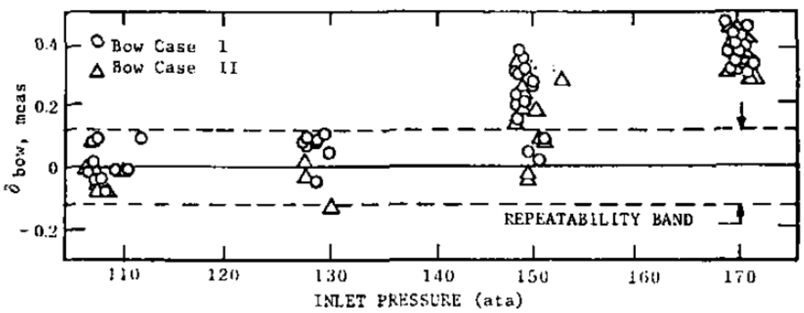


Figure 1: Bow effect parameter *vs.* inlet pressure. Copied from [2] (Fig.4), in the paper [9].

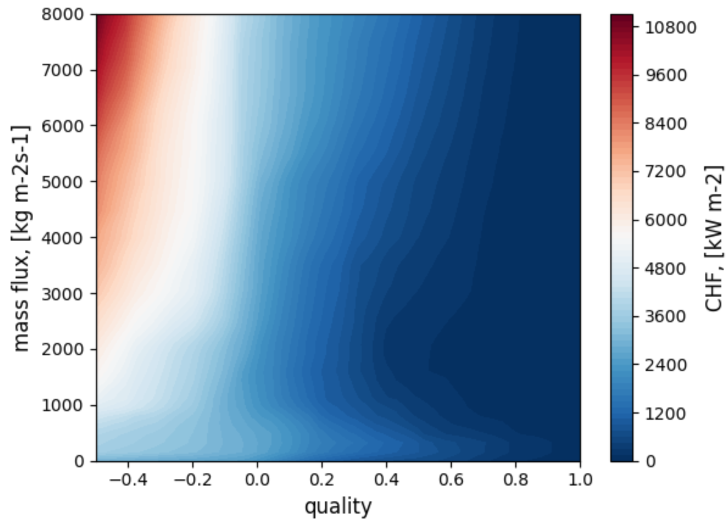
2. *In page 3, what are the reasons that the HTRF results on the effect of thimble tube were more significant compared with other studies?*
The presence of unheated rods in a bundle (control rod, guide thimbles etc.) has a significant effect on the cooling efficiency. It influences CHF and acts both as a cold wall effect and as a hydraulic diameter effect. We corrected our sentence following the conclusions in [2, 3]. In both papers, authors concluded that the reduction of CHF for rod bowing tests with a thimble tube is essentially the same as for rod bowing tests without an unheated rod.

3. *At the third line in page 5, "mass flux" should be modified to "mass flow rate".*
Corrected.

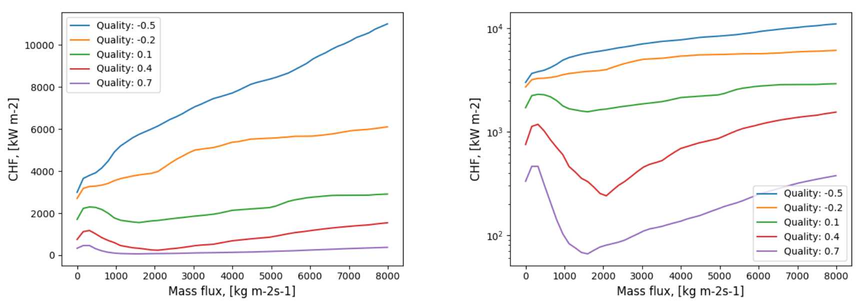
4. *In page 7, the second screening seems to be unreasonable. Why do we need to exclude for wrong prediction results? The data with the ratio greater than 1.5 can show drawback and weakness of the CTF code and/or CHF correlations. In addition, how about the data with the ratio of predicted to measured values less than 0.5?*
The way how filtering is done is presented in the Appendix of the paper, see Figure A.21. There are two cases when DNBR is too low and too high. All the results with CTF for each test can be found in the support link to the archive.

5. *At the 3rd line in page 8, "Figures 7, 6, 8, 9" should be changed to "Figures 6, 7, 8, 9".*
Changed.

6. *The "med" should be checked compared to "MED".*
Compared and corrected.



(a) Groeneveld LUT Critical heat flux distribution *vs.* mass flux and quality.



(b) (c)

Figure 2: Groeneveld CHF look-up table (LUT, 2006) at 156.2 bar, [4], in the paper [17].

7. *At 14th and 15th line in page 10, the text of "The reason for this ... at lower values" is not so clear and needs to be more specified. In general, the CHF increase rate is larger at low mass flux conditions that at the high mass flux conditions.*

We agree with reviewers' comment. In Figure 2 result of CHF predicted by Groeneveld look-up table is plotted. As can be seen, at low-quality flow conditions (< 0.15) and high mass fluxes (>5000 [kg m-2s-1]) inclination of the blue line is higher than for orange and green, Figure 2b. At high-quality flow conditions CHF dependence on mass flux is different, see Figure 2c. However, we wanted to show that the variation of CHF observed in the tests is mainly due to the change of mass flow rate in the distorted subchannels. It can also be seen in Figure 11 in the paper, where it is clear that only mass flow rates in the selected subchannels are varied; pressures and liquid temperature in the subchannels remain the same.

8. *It is difficult to understand the titles and meanings of Figs. 6 to 9. What data for what conditions did the authors plot in these figures? What are difference between Figs. 6 to 9 and Figs. 12 to 15? Data and meanings of Figs. 12 to 16 are quite clear but not in Figs. 6 to 9.*
In Section 4.1 in our paper, we studied how rod bowing configuration will affect the calculated critical power. In this case, the HTRF 166 test considered as a reference test. We used the same boundary conditions (i.e. temperature inlet, flow rate and pressure) as in the reference test for the same rod bowing configurations as in HTRF tests from 167 to 170. In Figures 6 to 9, we present the results of this comparison. We explain it in the text, and we also corrected the Figs 6–9 captions. We hope now it is more clear.

9. *Typo needs to be checked in "... be factored -in in future work" at the mid of page 23.*
Corrected.

10. *In the CFD calculations, the boundary condition for the thimble was given to adiabatic. This means that no heat transfer between the hot rod and the cold thimble. In general, the cold thimble can increase the CHF at low quality or decrease the CHF at high quality. Thus, the effect of cold thimble on the CHF depends on the flow regime at the CHF. The hot spot temperature in Fig. 18 (a) might become low if we consider the conduction heat transfer between the hot rod and the cold thimble. This needs to be modified in the calculation or to be discussed in the text.*
At the current stage, we cannot redo the CFD analysis. First, the primary goal of our paper is to show the performance of the subchannel code CTF in addressing rod bowing configurations. Second, CFD calculation has only support or/and illustrative role in this case. We wanted to show that in case of rod bowing to contact locally wall temperature is rising quite high, which cannot be captured by the subchannel code. We believe that CFD analysis of the rod bowing configurations deserves a separate paper.

11. *In the 2nd paragraph of page 28, "with 50% and 85% of the nominal gap" should be "with 15% and 50% of the nominal gap. The value of 85% are strange compared to 15% of HTRF 169 in page 4.*
Corrected in accordance with the comment.

12. *The last part of the 3rd paragraph, i.e., "For higher flow rates and pressure ...", needs to be checked. It is difficult to understand the text with the figures. The figures show the ratio of the predicted CHF to the measured CHF value.*

They do not show the measured CHFs.
Yes, we corrected our statement in the conclusions and excluded Figs. 12 and 13 from the conclusion, since, they showed CHF ratio between calculated and measured CHFs, as the reviewer also noticed it. In Figs. 8 and 9, however, CHF ratio is plotted for the CHF ratio between calculated and measured CHF in the reference test. We corrected following our conclusions.

13. *If the authors include a channel average value of equilibrium exit quality in Table A.2, it will be helpful for readers to guess a possible CHF mechanism, i.e., DNB or dryout type CHF.*
The format of the paper does not allow to include many parameters. If we add exit quality, it will be three additional columns. We will add these columns to the description of the archive, which will include all CTF input decks and post-processed results. This archive will be available to everyone.

Reviewer 3:

Grammatical: *Please be careful how you use the indefinite and definite articles; the entire manuscript has to be revisited in this regard.*
Entire manuscript was revisited and checked in this regard.

Citations: *COBRA-TF is widely used code with many different versions and CTF is only of those. I would recommend using "CTF" throughout the text if only CTF was used in this work. Also, please be more specific which version of CTF was used and make sure that it corresponds to the provided reference. I believe Ref. 18 is outdated.*
We added information about CTF code version and changed COBRA-TF to CTF in the text. Reference list is updated.

Technical:
1. *I don't fully agree with your approach to use a constant mixing coefficient within the entire bundle but appreciate the detailed explanation you have provided. For example, the sub-channel results show a fairly good agreement with the experimental data for the cases with partially blocked gaps while this is not the case for the fully blocked gaps. Certainly, we should not apply the same mixing coefficient in both cases. This is just a comment to the authors; it would be good if a discussion is added.*
We agree that applying a constant mixing coefficient within the entire bundle is questionable. In CTF there are two options for single-phase turbulent mixing coefficient either constant or according to Rogers and Rosehart correlation [5]. This correlation depends on the ratio of hydraulic diameters of adjacent subchannels, rod diameter and subchannel Reynolds number. The result of applying Rogers and Rosehart correlation presented in Figure 3. As can be seen, the performance of this correlation is worse in comparison to the model with the fixed mixing coefficient. Thus we decided to exclude this result from the final version of the manuscript. Applying various β constant for the different rod

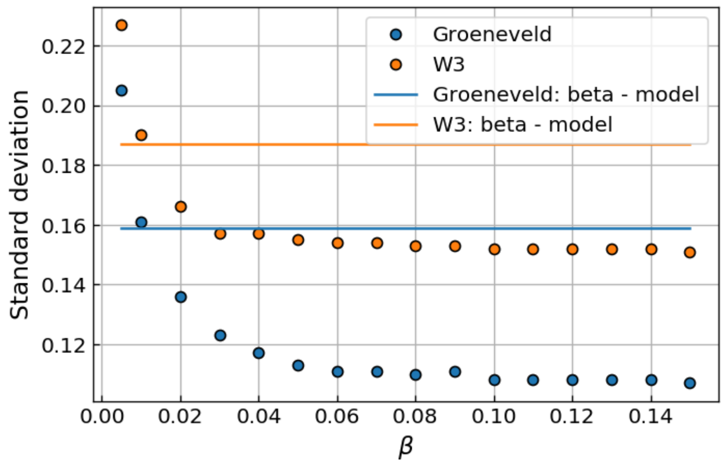


Figure 3: Standard deviation of the calculated critical power from the measured values vs the single-phase turbulent mixing coefficient β (points) and single-phase turbulent mixing model with Rogers & Rosehart correlation for the test HTRF 166.

bowing configurations does not make much sense either since distorted channels are only in the three penultimate sections and only four subchannels are affected by the one-rod displacement. Thus applying new β constant can improve modelling for the distorted channels, but can make much worse for all the other subchannels. Therefore, available (quite old ∼70's) turbulent mixing models in CTF require substantial improvement. Modern findings in modelling turbulent flows with DNS and LES methods can be applied for the further development of the turbulent mixing in the subchannel approach. We included partly this discussion in Section 4.1, in the part of selecting the mixing coefficient β.

2. Have you tried to determine the critical heat flux by following the experimental procedure (cladding temperature increase)? If so, how do CTF predictions compare to the W3 correlation and Groeneveld look-up tables?
The procedure for determining the CHF condition explained in section 4.1 second paragraph. We calculate the axial distribution of DNBR values for each rod and apply the gradient descent algorithm to find total power at which DNBR=1 for any rod and axial node. For predicting DNBR, two CHF models applied: W3 CHF correlation and Groeneveld CHF look-up table (LUT).

3. Please provide which CFD code was used in this study.
We added CFD code name and version in section 4.4. It is STAR-CCM+ v.11.6.

4. To my knowledge, the work reported in Sec. 4.5 is first-of-a kind. If you are aware of other similar investigations, please provide references.

In the framework of burnup credit, a study about the effect of fuel pin bowing to the final material inventory has been conducted [6]. In that study, a 3-dimensional 3×3 pin-cells lattice was modelled with the central pin bowed using a cosine profile (maximum displacement at the middle of axial elevation). The bowed pin was burned using an intra-pin fuel material discretization made of 4 radial layers, 8 azimuthal sectors and 40 axial segments, meaning that each segment was burned independently. In our model we do not consider burn-up effects, as well as 3-dimensional effects; however, the power inside the target fuel pin has been calculated using a mesh resolution of 20 radial layers and 16 azimuthal sectors.

Reviewer 4:

The paper presented a sub-channel analysis by taking bowing of the rods into account. The authors used the test data conducted at HTRF to carryout sub-channel analysis. In addition, a CFD analysis is also presented to analyze local temperature and flow distribution. The paper is in acceptable form with revision by taking care following points.

1. *Mention the subchannel no (13 or 19) that is used for the analysis in the section-3 of the paper and also mention wherever appropriate.*

In Figure 1 the positions of the selected subchannels 13 and 19 are presented.

2. *Mean deviation does not tell a complete story for prediction so it would be better if the discussion would involve mean absolute deviation.*

In the definition of mean absolute deviation, there is a choice of selecting the central point. It can be the mean, median, mode, or the result of another measure of central tendency. In our case, we selected the mean value as a central point, which is the most logical and natural choice in our analysis. We believe that choosing another central point will not give any advantages.

3. *Is it possible to make a direct comparison of 166 -167/168 bowed/straight test data to the calculated data with the Cobra-TF. How was the heat flux and power calculated in the tests. Is it based on the axial area weighted average. If so, for subchannel analysis three different analysis needs to be carried out, one for reduced area channel, second for the enlarged area subchannel and third for the straight subchanels. And to make a direct comparison axial area weighted average power needs to be compared.*

First question. We think it is not possible to make a direct comparison between reference test 166 and all others since boundary conditions are not the same.

Second question. In the tests, they determine critical power from which they can derive rods heat flux knowing rods radius and heated length. For the rod bowing configurations when the flow area of a subchannel has changed the variation of the rod heated area is negligible in this case.

4. *Section 4.1 Figure 10 discussion: There is no significant change in the spread of the data due to the bowing.*

That is true, spread remains almost the same, but there is a shift due to rod bowing, this is what we wanted to show, and this is the primary purpose of using boxplots here.

5. *A section should be added to show the computational domain and validation of the computational model. These are the few references that can be used for validation of the CFD model.*
a. https://doi.org/10.1016/j.nucengdes.2007.08.003
b. https://doi.org/10.1016/j.applthermaleng.2017.02.020
c. https://doi.org/10.1016/j.nucengdes.2009.11.031
d. https://doi.org/10.1016/j.pnucene.2013.08.012
Our paper is focused more on the performance of the subchannel code CTF in modelling rod bowing in a tube bundle. CFD and neutronic calculations have a support function as illustrative simulations only. We reckon that more detailed CFD and neutronic analysis required for more realistic cases, and such study deserves a separate publication.

References

[1] D Reddy and C Fighetti. Parametric study of CHF data, vol. 3: Critical heat flux data. np-2609. *Electric Power Research Institute, Palo Alto, CA*, Jan. 1983.

[2] Yoichi Nagino, Nobuhiro Shodai, Chiehiro Matsumoto, and Masao Ueji. Rod bowed to contact departure from nucleate tests in coldwall thimble cell geometry. *Journal of Nuclear Science and Technology*, 15(8):568–573, 1978.

[3] Xiao Zejun, Song Xianhui, Lang Xuemei, Bai Xuesong, Ma Jieliang, Wang Pengfei, and Chen Bingde. Experimental research progress on critical heat flux of Chinese PWR. *Nuclear Engineering and Design*, 229(2):213 – 222, 2004.

[4] DC Groeneveld, JQ Shan, AZ Vasić, LKH Leung, A Durmayaz, J Yang, SC Cheng, and A Tanase. The 2006 CHF look-up table. *Nuclear Engineering and Design*, 237(15):1909–1922, 2007.

[5] J.T. Rogers and R.G. Rosehart. Mixing by turbulent interchange in fuel bundles. correlations and influences. In *ASME*, pages 1–12, 1972. Paper 75-HT-31.

[6] J. Li, D. Rochman, J. Herrero, A. Vasiliev, H. Ferroukhi, A. Pautz, M. Seidl, and D. Janin. UO2 fuel pin bowing effects on isotopic concentrations. *Annals of Nuclear Energy*, 105:361 – 368, 2017.