

ON THE EVALUATION OF THE PRESSURE LOSSES IN A LEAD-BISMUTH-EUTECTICS COOLED FUEL ASSEMBLY WITH TRACE AND SUSA

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Abstract

The prediction of the pressure drop in a pool-type reactor operated with lead-bismuth-eutectics is of crucial importance. A pressure drop of e.g. 1 bar is equivalent to a lead-bismuth-eutectics column of about 1 m, which has a big influence on the financial aspects of the design proposal. The paper presents results on the hydraulic evaluation of a fuel assembly with the emphasis on uncertainties and variations of relevant parameters like the mass flow rate, form, and friction loss coefficients. With the subsequent uncertainty and sensitivity study, in connection with thermal hydraulic investigations, the influence of these uncertain parameters was evaluated.

1. Introduction

In the frame of the ongoing European project to establish a Central Design Team (CDT) for the FAst Spectrum Transmutation Experimental Facility (FASTEF) within the seventh framework program of EURATOM [1], researchers from Europe as well as from Asia work together at SCK·CEN (Mol, Belgium). The R&D is focused on various tasks like the neutronic and thermal hydraulic evaluation of the core, material issues, the design of the primary and secondary circuits, the implementation of an accelerator, the design and incorporation of in-pile test sections, etc.

One challenge of the current design process is the integration of the primary system into the main vessel. In the FASTEF pool-type configuration the cold and hot leg are separated by the diaphragm. The elevation difference between the free surfaces of the legs corresponds mainly to the pressure drop in the core section. An increase of the pressure drop by e.g. 1 bar would increase the level difference by about 1m ($\rho_{\text{LBE}} \approx 10000 \text{ kg/m}^3$). Hence, the height of the vessel is a function of the core pressure drop. Therefore, results presented in this paper are related to the hydraulic evaluation of a proposed fuel assembly (FA) design for FASTEF.

A comprehensive, thermal hydraulic evaluation of the FA design was performed with the system code TRACE to predict the pressure drop. Thereby, new physical models for the pressure drop were implemented into TRACE. Since the pressure drop is a function of time (due to changing parameters like the wall roughness), an evaluation of the FA was done at begin of cycle (BOC) and at end of cycle (EOC) as limiting cases. In addition, the investigation differentiates also between the average assembly (AVG) and the hot one (HOT) to include the different power levels. The effects of the variation of these and other uncertain parameters are analysed with SUSA. The information gained from this uncertainty and sensitivity study is useful to optimize the FA design.

2. Description of the FASTEF fuel assembly

The FA of FASTEF, given in Fig. 1, has a hexagonal geometry with a wrapper and currently 127 fuel pins, equipped with wire wraps for the mechanical support in radial direction. By means of spacer grids at the top and the bottom, the pins are axially held in place. The total length of the FA is 2 m, whereas the length of the inlet section is 0.2 m, the pin section is 1.4 m and the outlet section is 0.4 m. An overview of key features of the FA is given in Tab. 1.

As one can see in Fig. 1, the FA is characterized by various changes of the flow area (grids, expansions and contractions). The FA is divided into 8 sections with 8 K-factors. These K-factors are: K1 - inlet, K2 - conical diffuser, K3 - sudden expansion, K4 - lower spacer, K5 - upper spacer, K6 - sudden contraction, K7 - conical nozzle, K8 - outlet.

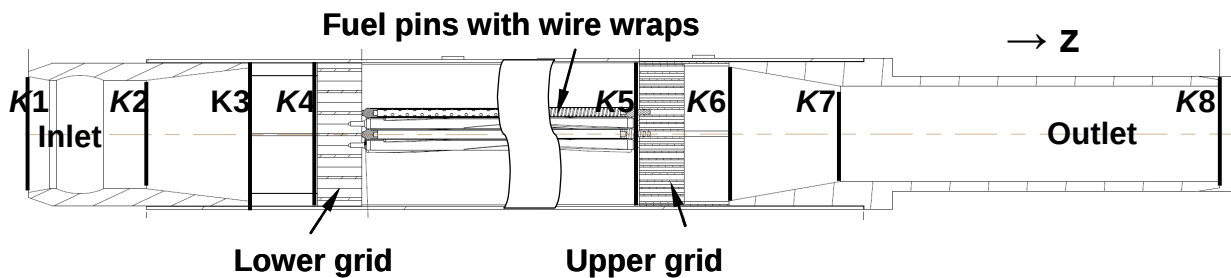


Figure 1 Axial cut through the present FA design

Table 1 Key parameters of the present FA design

Length of FA [m]	2.0
Length of fuel pin [m]	1.4
Active length [m]	0.6
Number of fuel pins	127
Pin diameter [m]	$6.55 \cdot 10^{-3}$
Pitch over diameter	1.2977
Hydraulic diameter (pin section) [m]	$4.008 \cdot 10^{-3}$
Mass flow rate [kg/s]	72.35
Power ratio (hot/average)	1.348
Wire pitch factor	40
Wire pitch [m] (Pin diameter x Wire pitch factor)	0.262

3. Brief description of TRACE and SUSA

3.1 TRACE

The best-estimate system code TRACE (TRAC/RELAP Advanced Computational Engine) is the current reference code of the United States Nuclear Regulatory Commission (U.S. NRC) related to thermal hydraulic analyses of operational transients as well as of loss of flow accidents of LWRs [2]. TRACE follows a component based approach allowing the user to model common plant components like pipes, pumps, vessels, etc. operated with different fluids like water and

LBE. Using a finite volume method, the partial differential equations describing the six equations for mass, momentum and energy conservation are solved. A Newton-Raphson iteration scheme is applied to the finite-difference equations describing hydrodynamic phenomena. The fluid dynamic equations in the spatial components are solved with a multi-step time differencing procedure while the equation for the heat transfer is solved using semi-implicit time-differencing schemes.

Since the KIT/INR takes part in the ongoing Code Application and Maintenance Program (CAMP) of the U.S. NRC, the TRACE source code is available and can be used for comprehensive validation and verification studies. This is essential for the present analysis since the physical models presented in the next section are about to be implemented into the TRACE source code. Investigations for the validation of TRACE related to lead and lead-alloy coolants have shown that code changes are necessary in order to simulate experiments [3, 4].

3.2 SUSAS

The SUSAS (Software for Uncertainty and Sensitivity Analysis) program has been developed by the GRS (Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH) [5, 6]. This tool can be used to evaluate the influence of input parameter variations on selected output parameters, following the input error propagation approach by means of probabilistic methods.

The number of runs (n) in order to satisfy the statistical fidelity is connected to the probability content (α) and confidence level (β) by a formulation derived by Wilks [7], see Eq. 1. This Wilks formula is thereby independent of the number of uncertain parameters, as shown in the following equations for the two-sided tolerance limit.

$$1 - \alpha^n - n \cdot (1 - \alpha) \cdot \alpha^{n-1} \geq \beta \quad (1)$$

In SUSAS, different measures are used to evaluate the sensitivity of input parameter changes on output parameters. These measures are: Pearson's product-moment coefficient, Blomquist's medial correlation coefficient, Kendall's rank correlation coefficient and Spearman's rank correlation coefficient. These four coefficients can be expressed in their ordinary form (ORD), as partial correlation coefficient (PCC) and as standard regression coefficient (SRC). The definition and the details of these measures can be found in open literature.

3.3 TRACE/SUSAS interface

This system was used in prior investigations and the results showed the necessity of uncertainty and sensitivity evaluation in the frame of best-estimate thermal hydraulic code validation as well as the applicability of the presented TRACE/SUSAS system [8, 9].

The communication between TRACE and SUSAS is based on a three-step data exchange. In a first step, the uncertain parameters of the TRACE input deck and of the physical models in the TRACE code are identified. These parameters along with their references values, the minimal, and the maximal values are given to SUSAS. The probability density functions (PDF), including information on the type of distribution, are also defined for all parameters. By means of Monte

Carlo sampling methods n values for each uncertain parameter are created following the distribution of the PDF. In the present case n is equal to 200 and hence the 95/95 statement for α and β is fulfilled according to Eq. 1.

The second step is the creation of 200 TRACE input decks, including input parameters as well as code parameters, according to the information gained from SUSA. These 200 input decks are then executed and selected information is extracted from the respective output files and stored in a new SUSA input file.

The third and final step is the actual uncertainty and sensitivity analysis. The uncertainty analysis evaluates the lower and upper uncertainty band of the output parameter - in the present investigation, the pressure drop - together with other statistical parameters like the mean and median value and the standard deviation. The sensitivity analysis identifies the input parameters with the highest influence on the pressure drop in a quantitative way by calculating sensitivity coefficients.

4. Physical models for the pressure drop

The local pressure drop (Δp_{local}) for single phase flow can be evaluated via the following simple formulation (ρ is the density, v is the velocity, l is the length and d the hydraulic diameter).

$$\Delta p_{\text{local}} = \frac{1}{2} \cdot \sum \left[\rho \cdot v^2 \cdot \left(f \cdot \frac{l}{d} + K \right) \right] \quad (2)$$

The total pressure drop can be calculated by adding all local pressure losses caused by friction factors (f) and form loss coefficients (K). For the calculation of the f and K -factor the literature offers a variety of options. Therefore, reference correlations are needed. With respect to the pin section, correlations developed by Rehme [10] were used for the wire wraps and the spacer grids. The other K -factors were calculated based on the recommendations of Idelchik [11].

4.1 Friction factor models

In order to include the effect of the wire wrap on the pressure drop, the TRACE model calculating the friction factors was changed. The standard friction factor correlation in TRACE is the Churchill correlation [12], Eqs. 3 and 4.

$$f_{\text{Churchill}} = 8 \left[\left(\frac{8}{\text{Re}} \right)^{12} + \frac{1}{(a)^{1.5}} \right]^{\frac{1}{12}} \quad (3)$$

$$a = \left\{ 2.475 \cdot \ln \left[\left(\frac{7}{\text{Re}} \right)^{0.9} + 0.27 \cdot \left(\frac{\Delta}{d} \right) \right]^{-1} \right\}^{16} + \left(\frac{3.753 \cdot 10^4}{\text{Re}} \right)^{16} \quad (4)$$

where Δ is the wall roughness [m] and d the hydraulic diameter [m].

But this correlation does not account for the wire wrap. Therefore, a correlation developed by Rehme [10] was implemented into TRACE, Eqs. 5 and 6. That correlation is well known and widely used in the nuclear community because of its wide range of applicability and good results compared to experiments [13]. Since the TRACE input does not foresee parameters like the number of rods (N_r) or the wire pitch (H), the correlation was hard-coded with fixed parameters. An additional routine makes sure that this correlation is only used in the pin section. The inlet and outlet section of the FA are described with the standard Churchill correlation.

$$f_{\text{Rehme}} = \left(\frac{64 \cdot F^{0.5}}{\text{Re}} + \frac{0.0816 \cdot F^{0.9335}}{\text{Re}^{0.133}} \right) \cdot \frac{N_r \cdot \pi \cdot (D_{\text{rod}} + D_{\text{wire}})}{S_t} \quad (5)$$

$$F = \left(\frac{P_t}{D_{\text{rod}}} \right)^{0.5} + \left[7.6 \cdot \frac{(D_{\text{rod}} + D_{\text{wire}})}{H} \cdot \left(\frac{P_t}{D_{\text{rod}}} \right)^2 \right]^{2.16} \quad (6)$$

Where D_{rod} is the pin diameter [m], D_{wire} is the wire diameter [m], H is the wire pitch [m], N_r the number of rods, P_t is the rod pitch of the wire wraps ($= D_{\text{rod}} + 1.0444 \cdot D_{\text{wire}}$) [m] and S_t is the total wetted perimeter [m].

The disadvantage of this correlation is the missing connection to the wall roughness. Since the wall roughness has an impact, especially with a small hydraulic diameter as in this case and an increased wall roughness at end of cycle, it needs to be considered in the simulations. Therefore, the Churchill correlation was used to calculate the friction factor for a rough pipe ($\Delta > 0.0$ m) and a smooth pipe ($\Delta = 0.0$ m). The ratio of the two friction factors was multiplied with the Rehme correlation, see Eq. 7. At a FASTEF FA typical Reynolds number of about 50000 the ratio is about 1.2 for a wall roughness of 5 μm used at EOC. Figure 2 shows the influence of the Churchill ratio on the friction factor correlation of Rehme.

$$f = f_{\text{Rehme}} \cdot \frac{f_{\text{Churchill}}^{\text{rough}}}{f_{\text{Churchill}}^{\text{smooth}}} \quad (7)$$

4.2 Form loss coefficient models

For the spacer grids, a correlation proposed by Rehme was used [10], Eq. 8. This correlation consists of a Reynolds dependent term and a correction term to account for the encumbering of the spacer area (A_{grid}) on the undisturbed flow area ($A_{\text{undisturbed}}$).

$$K_{\text{spacer}} = \left[3.5 + \left(\frac{73.5}{\text{Re}^{0.264}} \right) + \left(\frac{2.79 \cdot 10^{10}}{\text{Re}^{2.79}} \right) \right] \cdot \left(\frac{A_{\text{grid}}}{A_{\text{undisturbed}}} \right)^2 \quad (8)$$

Concerning the sudden expansion, the literature provides only one correlation. This correlation puts the flow areas before (A_{before}) and after (A_{after}) the expansion in a ratio, Eq. 9.

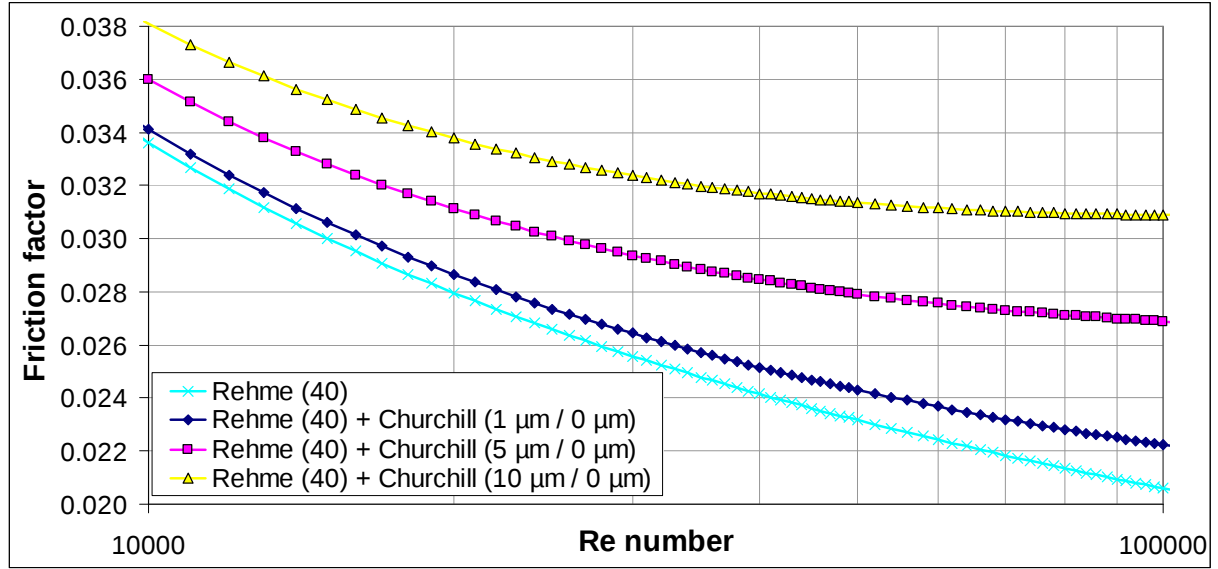


Figure 2 Impact of the Churchill ratio on the friction factor as a function of the Reynolds number and the wall roughness with a constant wire pitch factor (40)

$$K_{\text{expansion}} = \left(1 - \frac{A_{\text{before}}}{A_{\text{after}}}\right)^2 \quad (9)$$

The situation regarding the sudden contraction is different. Several correlations can be found in open literature. The approach of Idelchik, given in Eq. 10 is the reference one.

$$K_{\text{contraction}}^{\text{reference}} = 0.5 \cdot \left(1 - \frac{A_{\text{after}}}{A_{\text{before}}}\right) \quad (10)$$

Since many correlations are available for the sudden contraction [9], the ones predicting the lowest and the highest values are used to get the minimum and maximum value, respectively. With a flow area ratio of 0.77 a correlation mentioned in the TRACE manual [2], Eq. 11 was identified as the one giving the lowest.

$$K_{\text{contraction}}^{\text{low}} = 0.5 - 0.7 \cdot \left(\frac{A_{\text{after}}}{A_{\text{before}}}\right) + 0.2 \cdot \left(\frac{A_{\text{after}}}{A_{\text{before}}}\right)^2 \quad (11)$$

A correlation, Eq. 12, found in the VDI Waermeatlas [14] predicted the highest value.

$$K_{\text{contraction}}^{\text{high}} = 0.4875 - 0.3991 \cdot \left(\frac{A_{\text{after}}}{A_{\text{before}}}\right) \quad (12)$$

For the inlet and outlet section, and the conical parts, the K -factors are derived from diagrams and tables provided by Idelchik. The evaluation of these factors is given in the following section together with the numbers calculated for the spacers and the sudden expansion/contraction.

5. Uncertainty quantification and modelling

In the present study, the determination of the uncertainty bands of the input parameters is mainly based on engineering judgment (experience, comparison to similar components/structures with known uncertainties, etc.) due to the missing information of the distribution of the empirical correlations. Also, varying parameters like the mass flow rate complicate the evaluation of the parameter range. The values for all, in total 16, uncertain parameters are listed in Tab. 2 for the average assembly at BOC and EOC, and the hot assembly at BOC and EOC.

The uncertainty of the friction factor is related to the wall roughness and the wire pitch. At BOC the reference wall roughness is $1.0\ \mu\text{m}$ whereas the one for EOC is $5.0\ \mu\text{m}$. The uncertainty for the values was assumed to be $\pm 1.0\ \mu\text{m}$ for both cases. The reference value for the wire pitch factor is 40. It is assumed that due to the manufacturing and operation the wire pitch factor will not be constant and is therefore varied between 39 and 41.

The K -factors of the spacer grids are 0.510 for the lower one ($K4$) and 0.824 for the upper one ($K5$). Due to the difficulties in determining the grid cross section, an uncertainty of $\pm 5\%$ is considered. With a ratio of 0.78 for the present FA design, a K -factor of 0.049 was calculated for the sudden expansion ($K3$). An uncertainty of $\pm 5\%$ was considered. The reference value for the sudden contraction ($K6$) is 0.114. The minimal value is 0.079 and the maximal value is 0.179.

For the inlet of the FA ($K1$), the approach of Idelchik gives a maximum value of 0.5 for sharp edges. In case the edges are rounded or equipped with a small nozzle, the value can be reduced to 0.26 for the present geometry. Therefore, the reference and maximum value is set to 0.5 while the minimum value is 0.26. The outlet section ($K8$) can be quantified with a value of 1.0 with the condition that the velocity profile is uniform. Otherwise, the value can be much higher. Thus, the reference and the minimal value are 1.0 while the maximum one is 1.5.

The K -factors for the conical diffuser ($K2$), right before the lower spacer and the conical nozzle ($K7$), right after the upper spacer are 0.105 and 0.050, respectively. Due to the difficulties in evaluating the area transition and the coarse net of data points in the tables of Idelchik, an uncertainty of $\pm 5\%$ was taken into account for both values.

The operating parameters mass flow rate and power are afflicted with uncertainties, too. The power is 1.4706 MW for the average FA and 1.9824 MW for the hot one (power peaking factor is 1.348). An uncertainty, $\pm 2\%$ have been estimated (a change in power will change the temperature profile and the density along the FA, and hence the pressure drop). In the present study, the average mass flow rate per FA at BOC is 72.35 kg/s. An uncertainty of $\pm 2\%$ seems to be appropriate to account for instabilities in the pump speed or the distribution to the several FAs. Besides the uncertainty, the mass flow rate is slightly lower for the EOC-HOT FA due to abrasion of the pump impellers and the corrosion and oxidation of the structural material.

The last set of uncertainties is related to the thermophysical properties of LBE. The properties have been adapted to the recommendations of the OECD [15] and the details about the uncertainties have been adopted. Thereby, the correlations in the TRACE code have been multiplied with uncertainty factors. In case of the thermal conductivity, the specific heat and the dynamic viscosity the factor varies between 0.95 and 1.05. For the density the factor is between 0.99 and 1.01.

The TRACE model of the FA consists of 84 cells with cell lengths ranging from 8 to 75 mm in order to represent the geometrical variations along the FA. Boundary conditions are given for the mass flow rate (inlet), the pressure (outlet) and the power (wall heat structure).

6. Results of the pressure drop analyses

Absolute and relative results of the pressure drop for the four scenarios are given in Tab. 3 (reference: BOC-AVG scenario). The total pressure drop for the reference case is 2.1789 bar. The most extreme cases give 2.0399 bar and 2.6168 bar which is about 94 % and 120 % of the reference case. With an envisaged pressure drop of 2.5 bar, the current design is at its limits. That means that there is almost no margin for increasing the FA mass flow rates. For the presented design study, with an average coolant heat up of 140 K and a heat up of 180 K for the hot assembly, a homogenised core outlet temperature is hard to realize.

The comparison of the different contributors to the total pressure drop show that 75 to 80 % of the total pressure drop is due to friction. Such a high value can be expected since the fraction of the pin section is 1.4 m of the 2.0 m (70 % of the total length). That means that 1.0 m pin section is equivalent to roughly 1.2 bar. The variation of the pressure drop related to friction is identical to the one for the total pressure drop (94 – 120 %) since it is dominated by the frictional one.

The inlet and outlet section are 20 to 25 % of the total pressure drop. The inlet pressure drop varies from 78 to 104 % of the reference inlet pressure drop, while the outlet pressure drop is ranging from 96 to 148 %. The ratio of the pressure drop at the inlet and at the outlet is roughly 1:2, which is the ratio of the length of the inlet and outlet section. For the maximal scenarios, the outlet pressure drop is more than twice the inlet one since the K -factor has a bigger variation. In addition, the velocity in the outlet section is higher due to the smaller internal diameter. Hence, the impact of the K -factor on the pressure drop is even higher.

The comparison of the results for the average and the hot FA shows almost no difference for the BOC case. The difference between those two cases is the power. Hence, an increase of power without any other change has no influence on the results since the subsequent change in density is not enough to provoke any significant difference. For the EOC case the mass flow rate was changed, too, leading to bigger differences between the average and the hot FA.

The comparison of the BOC and EOC scenarios shows a significant difference in the results. Table 2 shows that mainly the frictional part has changed. The difference is related to the different values for the wall roughness. An increase from 1 to 5 μm yields an increase > 0.2 bar which is 13 – 20 % of the frictional part. Such an increase is expected since the Churchill ratio is in the order of 20 % for the comparison of smooth pipe ($\Delta = 0.0\mu\text{m}$) and a rough pipe ($\Delta = 5.0\mu\text{m}$). Since at BOC the wall roughness is 1.0 μm , the value is therefore smaller (13 – 20 %).

Table 2 Documentation of the uncertain parameters (best estimate, minimum and maximum) for the different scenarios

Parameter (P)		BOC-AVG			BOC-HOT			EOC-AVG			EOC-HOT		
		BE	Min	Max	BE	Min	Max	BE	Min	Max	BE	Min	Max
1	<i>P</i> [MW]	1.4706	1.4412	1.5000	1.9824	1.9427	2.0220	1.4706	1.4412	1.5000	1.9824	1.9427	2.0220
2	<i>m</i> [kg/s]	72.350	70.903	73.797	72.336	70.889	73.782	72.350	70.903	73.797	70.758	69.343	72.174
3	<i>k</i>-LBE	1.00	0.95	1.05	same as BOC-AVG								
4	<i>cp</i>-LBE	1.00	0.95	1.05									
5	<i>ρ</i>-LBE	1.00	0.99	1.01									
6	<i>η</i>-LBE	1.00	0.95	1.05									
7	<i>Δ</i> [μm]	1.00	0.00	2.00	1.00	0.00	2.00	5.00	4.00	6.00	5.00	4.00	6.00
8	WPF	40.0	39.0	41.0	same as BOC-AVG								
9	<i>K</i>-factor 1	0.5000	0.2600	0.5000									
10	<i>K</i>-factor 2	0.1051	0.0998	0.1103									
11	<i>K</i>-factor 3	0.0493	0.0469	0.0518									
12	<i>K</i>-factor 4	0.5100	0.4869	0.5424									
13	<i>K</i>-factor 5	0.8240	0.7825	0.8776									
14	<i>K</i>-factor 6	0.1140	0.0788	0.1794									
15	<i>K</i>-factor 7	0.0500	0.0475	0.0525									
16	<i>K</i>-factor 8	1.0000	1.0000	1.5000									

Table 3 Results of the uncertainty analysis for the different scenarios in absolute and relative values

	BOC-AVG			BOC-HOT			EOC-AVG			EOC-HOT		
	BE	Min	Max	BE	Min	Max	BE	Min	Max	BE	Min	Max
<i>Δp</i> – total [bar]	2.1789	2.0399	2.3893	2.1789	2.0429	2.3952	2.3987	2.2731	2.6168	2.3088	2.1880	2.5185
<i>Δp</i> – friction [bar]	1.7081	1.6046	1.8322	1.7110	1.6063	1.8361	1.9241	1.8232	2.0494	1.8528	1.7559	1.9731
<i>Δp</i> – inlet [bar]	0.1678	0.1302	0.1746	0.1677	0.1301	0.1746	0.1738	0.1358	0.1808	0.1664	0.1301	0.1732
<i>Δp</i> – outlet [bar]	0.2987	0.2946	0.4427	0.3002	0.2961	0.4450	0.3008	0.2968	0.4449	0.2896	0.2857	0.4283
<i>Δp</i> – total¹	1.00	0.94	1.10	1.00	0.94	1.10	1.10	1.05	1.20	1.06	1.01	1.16
<i>Δp</i> – friction¹	1.00	0.94	1.07	1.00	0.94	1.07	1.13	1.07	1.20	1.08	1.03	1.16
<i>Δp</i> – inlet¹	1.00	0.78	1.04	1.00	0.78	1.04	1.04	0.81	1.08	0.99	0.78	1.03
<i>Δp</i> – outlet¹	1.00	0.99	1.48	1.01	0.99	1.49	1.01	0.99	1.49	0.97	0.96	1.43

¹ Relative values, compared to the values of the best estimate case of the average FA at BOC conditions.

Table 4 Sensitivity coefficients for the pressure drop (BOC-AVG)

Rank	Ordered sensitivity measures from ordinary correlations						Ordered empirical correlation ratios		Ordered correlation ratios on ranks	
	ORD	P	PCC	P	SRC	P		P		P
Total pressure drop										
1	0.7595	2	0.9997	2	0.7403	2	0.7814	2	0.7895	2
2	0.5092	16	0.9993	16	0.4960	16	0.5493	16	0.5370	16
3	0.3277	7	0.9987	7	0.3715	7	0.4218	7	0.4012	7
Frictional pressure drop										
1	0.8359	2	0.9998	2	0.8416	2	0.8540	2	0.8530	2
2	0.4776	7	0.9994	7	0.5217	7	0.5242	7	0.5147	7
3	-0.2144	8	-0.9965	5	-0.2109	5	0.3215	9	0.3309	9
Inlet pressure drop										
1	0.9162	9	0.9997	9	0.8977	9	0.9189	9	0.9241	9
2	0.3954	2	0.9976	2	0.3395	2	0.5004	2	0.4773	2
3	-0.1489	4	0.9906	12	0.1720	12	0.2961	4	0.2974	4
Outlet pressure drop										
1	0.9689	16	0.9997	16	0.9615	16	0.9698	16	0.9697	16
2	0.2540	2	0.9944	2	0.2244	2	0.3517	2	0.3461	2
3	0.1122	15	0.9331	15	0.6178	15	0.3076	15	0.3114	15

Table 4 shows the three input parameters (P) with the highest sensitivity coefficients as a function of the different measures. The indexing P is the same as in Tab. 2. Values between -0.4 and 0.4 are below significance and should be treated with caution. A negative number indicates that the pressure drop decreases with increasing input parameter, like with c_p or the wire pitch. One can see that all measures, except the PCC, give almost the same numbers for the same parameters. Only the PCC predicts numbers around unity. This measure evaluates the strength of the association between a dependent and an independent variable when the influences of all other independent variables are eliminated. This can have the disadvantage of giving parameters a high weighting even if the importance is not that high, as in the present example.

For the total as well as for the frictional pressure drop the mass flow rate has the highest impact. A variation of $\pm 2\%$ can cause a big difference between the minimum and the maximum pressure drop. Since the pressure drop dependence on the velocity is of quadratic nature, the impact, in particular, is therefore high. Depending on how constant the pump can deliver the nominal mass flow rate, the free LBE surface of the cold leg will move up and down.

The second most significant parameter is no. 16 which is the K -factor at the FA outlet. The reason is related to the rather wide range of that parameter, which has therefore a higher significance in the calculation of the sensitivity coefficient. That means also that there is a margin for lowering the pressure drop. In general, the inlet and outlet section, although responsible for only about 20 to 25 % of the total pressure drop can be the subject of design optimizations. This can be done by rounding the edges at the inlet/outlet or by reconsidering the spacer grid layout.

The third most important parameter is the wall roughness. Due to the small pin diameter (6.55 mm) the hydraulic diameter of the coolant channel is only 4 mm. The relative roughness (wall roughness/hydraulic diameter) is rather high and has hence a certain impact on the friction.

A look to the pressure drop at the inlet and outlet shows that the inlet K -factor and the outlet K -factor, respectively, are the main contributors. Also the mass flow rate has an impact since the friction will also take place there (inlet and outlet section are 30 % of the total length).

7. Conclusion

This present investigation deals with the evaluation of the pressure drop in a FA design proposal for FASTEF with special emphasize on the quantification of the uncertainties on the results. The paper shows, on one side, the necessity of the combined application of a thermal hydraulic best estimate code with a program to evaluate uncertainties and sensitivities of input. On the other side, the combined TRACE and SUSANA application predicted physically sound results for the pressure drop analyses.

The reference pressure drop is 2.18 bar and the minimum and maximum is 2.04 and 2.62 bar, respectively. The difference of roughly 0.6 bar is equivalent to a level variation of the cold leg of about 0.6 m. Based on the reference value, the pressure drop varies from 94 to 120 %. The analyses show also that the fraction of the friction in the pin section is 75 to 80 % of the total one. The remaining 20 to 25 % are related to the inlet and outlet. The difference between the AVG and the HOT FA is only a few percent while the difference between BOC and EOC is around 20 %.

The parameter variation with the highest significance was the one related to the mass flow rate. Besides the mass flow rate the K -factor at the FA outlet and the wall roughness are parameters where variations have a big influence on the pressure drop. Parameters like the power or the thermo physical properties of the LBE are unimportant for the present study.

One way of lowering the total pressure drop could be the increase of the wire pitch. But this can only be done after a detailed and comprehensive thermo-mechanical analysis identifies the limits in order to guarantee the fixation of the pins. For a full understanding of the coolant-structure interaction and the pressure drop one has to perform detailed experiments and CFD analyses. In case a reduction of the pin section is feasible (reduced gas plenum in the pins), the pressure drop can be reduced considerably. Other measures to lower the inlet and outlet pressure drop might include geometry changes like rounded edges, etc.

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