Experimental investigation of the pressure loss characteristics of the full-scale MYRRHA fuel bundle in the COMPLOT LBE facility

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ABSTRACT

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a flexible fast-spectrum research reactor under design at SCK•CEN, the Belgian Nuclear Research Center. MYRRHA is a pool-type reactor with Lead Bismuth Eutectic (LBE) as primary coolant. Conceived as an accelerator driven system prototype, it is able to operate in sub-critical mode. Operating in critical mode, MYRRHA is identified as the European Technology Pilot Plant for the Lead Cooled Fast Reactor which is one of the Generation IV reactor concepts.

The MYRRHA fuel assembly (FA) contains a hexagonal bundle of 127 cylindrical fuel pins surrounded by a hexagonal shroud or wrapper. The upper and lower ends of the shroud are connected to the inlet and outlet nozzles guiding the LBE coolant through the FA. Helical wire-spacers wound on the outer surface of each fuel pin, keep the fuel pins separated from one another in the bundle.

A full-scale mock-up of the MYRRHA FA was constructed and installed in the COMPLOT LBE experimental test facility at SCK-CEN, for the purpose of measuring the axial pressure drop across the assembly. Pressure measurements were taken at various axial positions within a single edge subchannel, using small tappings through the wall of the hexagonal housing, axially spaced in multiples of the wire-wrapper pitch. Additional pressure tappings were placed at the same axial height on different hexagonal walls, to investigate the variation of pressure in one cross-section of the fuel assembly and verify the presence of local maximum and minimum pressures due to the characteristic spiralling pressure and flow field induced by the wire-wrapped bundle assembly.

The paper will report on the experimental results. These are used to support the design and development of the MYRRHA reactor and are also compared with existing pressure drop correlations as well as numerical results from codes such as CFD.

KEYWORDS
MYRRHA, fuel assembly, pressure, experimental, COMPLOT

1. INTRODUCTION

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a flexible fast-spectrum research reactor under design at SCK•CEN, the Belgian Nuclear Research Center. MYRRHA is a pool-type reactor with Lead Bismuth Eutectic (LBE) as the primary coolant. Conceived as an accelerator driven system prototype, it is able to operate in sub-critical mode. Operating in critical mode, MYRRHA is identified as the European Technology Pilot Plant for the Lead Cooled Fast Reactor which is one of the Generation IV reactor concepts [1].

The pressure losses in the MYRRHA fuel assembly (FA) dominate the overall primary system pressure loss and so knowledge of the coolant pressure drop across the FA is crucial to determine the primary pump design dimensions and specifications during normal operation. Furthermore, knowledge of the pressure loss characteristics at low flow rates will allow designers to evaluate the possibility of passive decay heat removal.

The MYRRHA FA design, like many liquid metal fast reactor (LMFR) designs, uses the helical wire-spacer to preserve the spacing between the fuel pins and promote coolant mixing between adjacent subchannels. Numerous friction factor correlations for wire-wrapped fuel assemblies have previously been established by various authors on the basis of air, water and sodium experiments, mostly for a reduced number of fuel pins. These existing correlations have been evaluated by various researchers such as Bubelis and Schikorr [2], Chun and Seo [3] and perhaps most extensively by Chen and Todreas [4], to evaluate their relative performance with regard to available experimental pressure drop data. Yet, experiments with wire-wrapped bundles in LBE are limited and the different existing correlations exhibit varying degrees of accuracy dependent on the flow regime, bundle geometric parameters and wire-to-pin configuration (i.e. H/D and P/D). Therefore, to support the design and licensing of MYRRHA and test the relative performance of the existing friction factor correlations, an experimental campaign was setup at SCK•CEN to perform hydraulic testing of a full-scale mock-up of the MYRRHA FA in the large-scale COMPonent Loop Testing (COMPLOT) LBE facility at SCK•CEN.

The purpose of this paper is therefore to share the experimental pressure drop data for the MYRRHA fuel assembly bundle, and compare this pressure drop data with the most relevant existing friction factor correlations and CFD predictions.

2. EXPERIMENTAL FACILITY DESCRIPTION

The COMPLOT LBE facility is a closed-loop facility, designed to characterise the hydraulic behaviour of various full-scale MYRRHA components in LBE. The system is capable of circulating a maximum flow rate of 36 m^3/h of LBE. The loop is isothermal, meaning it operates at a constant LBE temperature for a given test, although the temperature can be varied up to a maximum of 400°C to investigate temperature effects. The temperature of the loop is maintained by means of electrical heat tracing of all components. Figure 1 illustrates a schematic of the COMPLOT loop with the constituent components, while the design assembly and as-built condition of the COMPLOT LBE facility is shown in Figure 2.

2.1. Fuel Assembly Test Section

The vertical test section in COMPLOT is representative of a single MYRRHA core position or in-pile section (IPS) at full height, with the LBE flowing upwards like in MYRRHA. The MYRRHA FA design consists of a hexagonal bundle of 127 cylindrical fuel pins surrounded by a hexagonal shroud or wrapper. The upper and lower ends of the shroud are connected to the inlet and outlet nozzles guiding the LBE coolant through the FA. Helical wire-spacers wound on the outer surface of each fuel pin, keep the fuel pins separated from one another in the bundle and promotes coolant mixing.

For the experimental full-scale mock-up, the COMPLOT FA test section itself represents only the inner profile of the MYRRHA FA, since it is only the internal hydraulics of the FA which needs to be representative and measured experimentally. Therefore, the hexagonal bundle is held between two half hexagonal shells welded together, and flanged between the inlet and outlet nozzle spool pieces. The modular design allows the bundle to be removed and the inlet and outlet nozzles can be modified and exchanged if necessary.

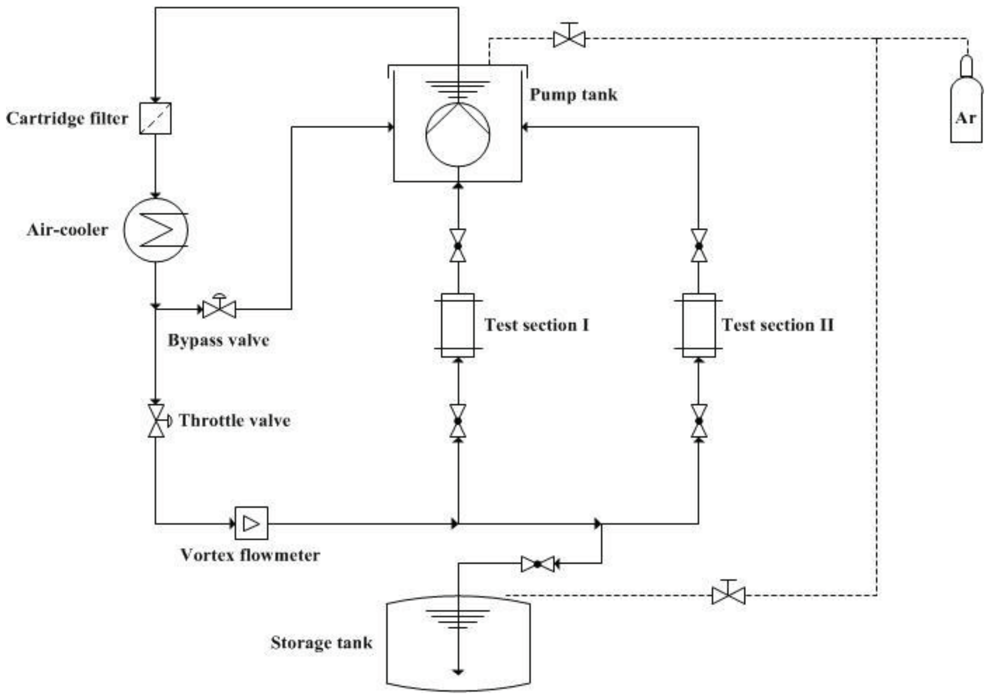


Figure 1. Schematic of the COMPLOT loop.

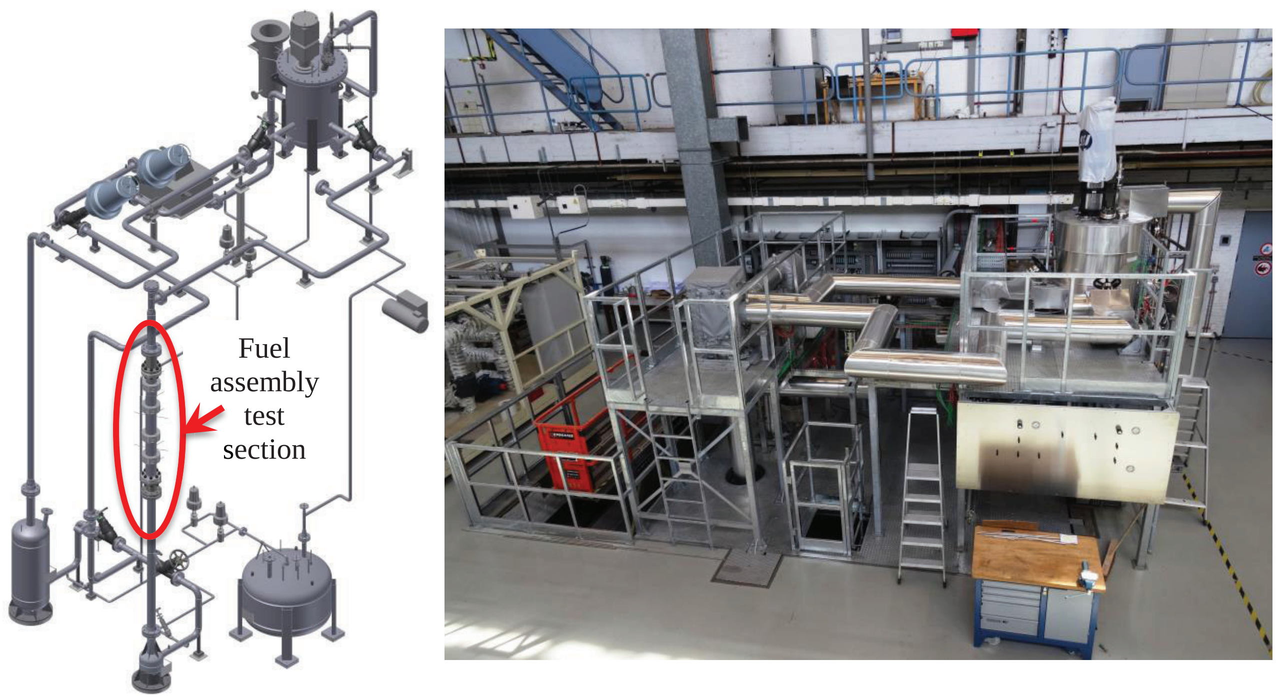


Figure 2. The COMPLOT loop: design assembly (left) and the as-built construction (right)

The geometric specifications of the FA bundle used in MYRRHA and the COMPLOT full-scale mock-up are given in Table I.

Table I. MYRRHA and COMPLOT bundle geometric specifications

Parameter	Symbol	Value	Units
Number of fuel pins	N	127	-
Pin length	L	1400	mm
Pin pitch	P	8.4	mm
Pin diameter	D_r	6.55	mm
Pitch-to-diameter ratio	P/D_r	1.282	-
Wire spacer diameter	D_w	1.8	mm
Wire-wrapper pitch	H	265*	mm
Wire lead-to-diameter ratio	H/D_r	40.458	-
Bundle flow area	A_{bdl}	3638.59	mm^2
Bundle wetted perimeter	P_{bdl}	3669.43	mm
Bundle hydraulic diameter	$D_{h,bdl}$	3.966	mm

The COMPLOT FA test section design assembly is shown in Figure 3, and the fuel pin bundle during and after the test section assembly is shown in Figure 4.

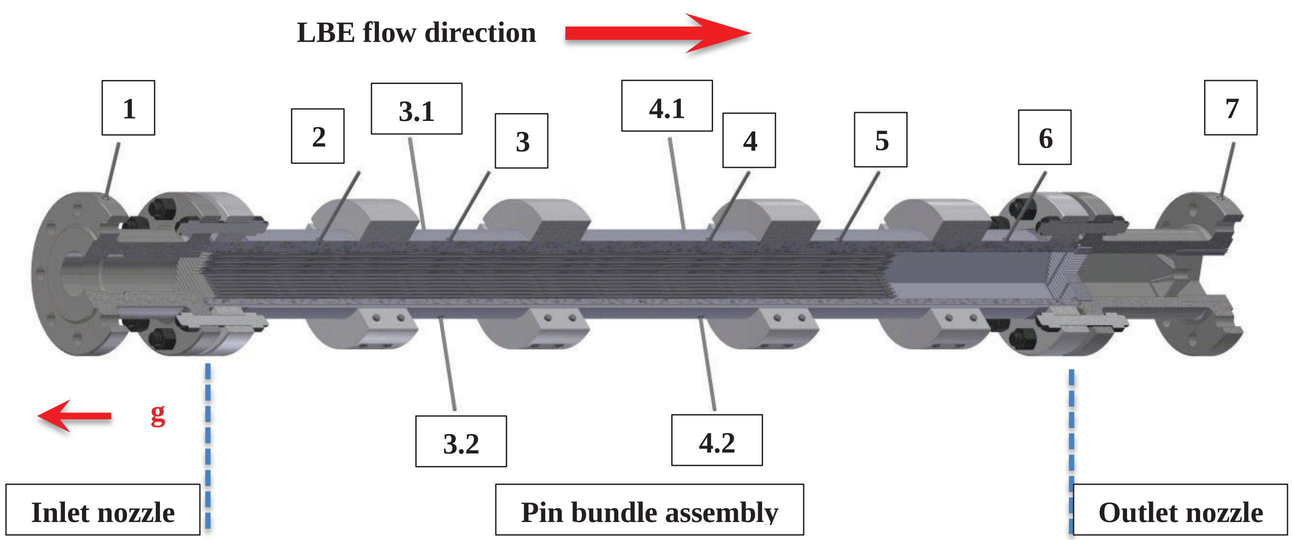


Figure 3. The COMPLOT fuel assembly test section.

The complete fuel assembly test section is equipped with a total of eleven pressure taps. A tap at the fuel assembly test section inlet (tapping #1) and outlet (tapping #7) is provided to allow for the measurement of the fuel assembly total pressure drop. The remaining nine pressure taps are located in the hexagonal

* The MYRRHA wire-wrapper pitch is 262 mm, however the COMPLOT fuel assembly bundle was assembled with a wire-wrapper pitch of 265 mm due to limitations during the assembly process.

bundle, made by small 2mm diameter holes drilled through the wall of the hexagonal housing. Four of these tappings (tappings #2, #3, #4, and #5) are positioned in the centre of a single edge rectangular subchannel, axially spaced in multiples of the wire-wrapper pitch. An additional two pressure tappings are placed at the same axial height of each of taps #3 and #4 respectively, but on different hexagonal walls. These additional tappings serve to investigate the variation of pressure in one transverse cross-section of the fuel assembly and verify the presence of local maximum and minimum pressures due to the characteristic spiralling pressure and flow field induced by the wire spacers.

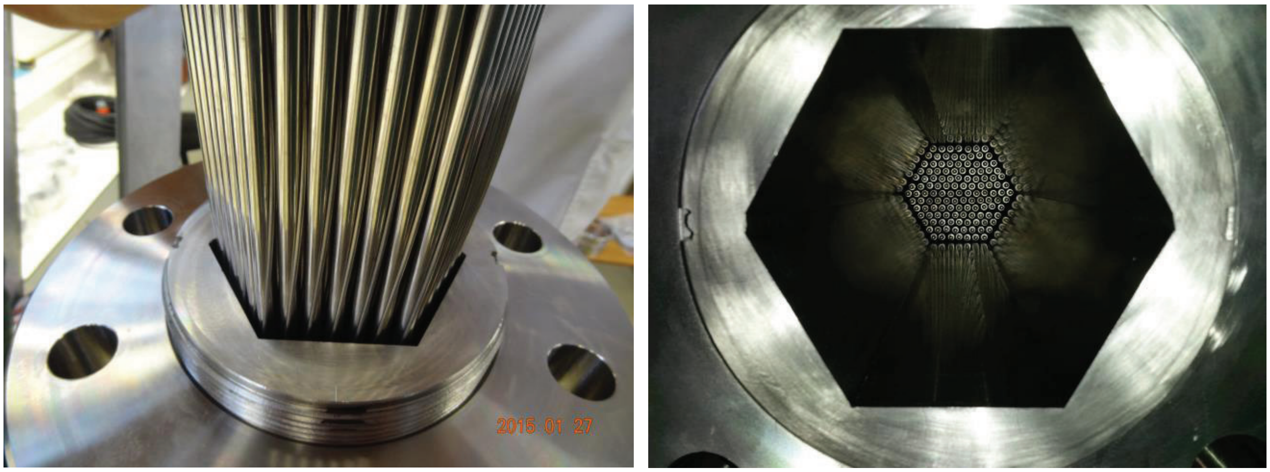


Figure 4. The COMPLOT fuel pin bundle during assembly (left) and after assembly (right).

The specific positioning of the pressure taps in the bundle assembly was chosen after analysis of the pre-test CFD simulations performed at NRG. A more detailed explanation of the pressure tap positioning is given in the subsequent section 2.3.

Although one of the primary objectives of this work is to determine the fuel assembly total pressure drop, this paper focuses on the pressure drop within the bundle only, and aims to compare the experimental bundle pressure loss data with existing friction factor correlations.

2.2. Instrumentation

The total volumetric flow rate through the fuel assembly test section is measured by means of a vortex flowmeter. This instrument exhibits an accuracy of 0.69% of the flow rate, at the MYRRHA nominal mass flow rate of 71.4 kg/s.

The temperature of the LBE is measured by means of two PT100 temperature sensors, mounted upstream and downstream of the test section, with the thermowell probes positioned in the centre of the piping. These sensors have a tolerance of ±1.3 °C at 200°C.

The fuel assembly total pressure drop and the pressure drop across specific sections of the fuel assembly, such as the fuel pin bundle and the inlet and outlet nozzles, are measured using Rosemount 3051 remote seal differential pressure transmitters. Two different transmitters with different measurement ranges are used, one for the larger differential pressure measurements (span of 2500 mbar) such as the total pressure drop, and the other for smaller pressure differences (span of 623 mbar). The accuracy of both instruments is 0.065% of the individual span.

The transmitter diaphragms are all mounted at the same elevation thereby eliminating the need to adjust for static pressure differences. Prior to each test, with no flow through the test section, the pressure transmitter readings are all checked and manually set to zero. In addition, the tubes connecting the transmitter diaphragms to the test section are all temperature controlled to the same temperature, therefore differences in pressure due to changes in LBE density are mitigated.

2.3. Pre-test CFD simulations

Due to the presence of the wire-wrapper, local axial and transverse pressure variations are expected within wire-wrapped bundle assemblies, based on previously published works such as the 19 pin water experiments performed at CEA by Lafay [5] and the associated CFD validation study by Bieder et al. [6]. These previously published results show the existence of an axial pressure oscillation within a rectangular peripheral subchannel that is periodic with the axial direction, the period of which corresponds to the helicoidal wire-wrapper pitch, provided that the flow is hydraulically well established. The magnitude of the local static pressure measurement is therefore also dependent on the wire-wrapper position relative to the pressure measurement tapping.

Pre-test CFD simulations of the MYRRHA 127 pin wire-wrapped fuel assembly were performed at NRG to gain some insight and visualisation of the flow field within the fuel bundle, particularly in the relevant subchannels. The CFD analysis aimed to provide information regarding the placement of the pressure measurement tappings. A complete fuel assembly, including the inlet and outlet headers and internal structures to fix the actual fuel pins was modeled with the commercial code STAR-CCM+. The fuel assembly was modelled using 11 million polyhedral cells in the rod bundle. A mesh sensitivity study was performed by Gopala et al. 2014 [7]. 0.2 million and 0.3 million cells were additionally required for the inlet header and outlet header respectively. The walls of the headers and the hexagonal wrapper were assumed to be adiabatic. A no-slip condition was applied to all walls. The SST k-ω turbulence model was applied and the wire shape was slightly modified in order to facilitate meshing to obtain a computationally feasible domain. The influence of this slight modification is studied in detail by Gopala et al. 2014 [7]. The heat production was modeled as a heat flux at the rod surface, which differs per rod according to the position in the fuel assembly. In accordance with the MYRRHA design, a mass flow rate of 71.4 kg/s was applied at the inlet, and a pressure outlet was set at the end of the outlet header. An LBE inlet temperature of 270°C was used in order to account for the maximum foreseen MYRRHA inlet temperature. The temperature difference between the experiment (200 °C) and the average bundle temperature in the simulation means a difference of less than 2% in the LBE density, so its influence on the pressure drop will be negligible.

Figure 5 illustrates three pressure contour plots from the CFD analysis, representing the transverse pressure distribution at three different axial heights, namely (from left to right in Figure 5) 1.75·H, 3.75·H, and 4.75·H wire-wrapper pitch lengths from the start of the wire-wrapper. In each contour plot, an obvious transverse pressure gradient is seen throughout the bundle cross-section, revealing distinct local minimum and maximum pressure regions on opposing walls of the hexagonal bundle, with a repeated and consistent maximum difference of ±12 kPa. It is also clear that the transverse pressure distribution at each of these axial heights is practically the same, which is expected since the contour plots are axially spaced in multiples of the wire-wrapper pitch. Further investigation of the CFD results shows that the axial evolution of the transverse pressure distribution is repeated as a continuous spiral, which propagates axially through the bundle, with a period corresponding to the wire-wrapper pitch.

The axial pressure evolution and the effect of the wire-wrapper at the bundle periphery is more evident when the axial pressure evolution within a specific rectangular edge subchannel is studied in more detail. Figure 6 (left) shows three pressure tappings at an axial level of 3.75·H on the COMPLOT fuel assembly test section, each centrally located in a rectangular edge subchannel at the azimuthal positions of 0°, 120°, and 300° respectively, as shown. Figure 6 (right) shows the CFD analysis results of axial pressure versus bundle length for each of the corresponding edge subchannels, where the periodic, oscillatory nature of the axial pressure drop in each edge subchannel is clearly evident.

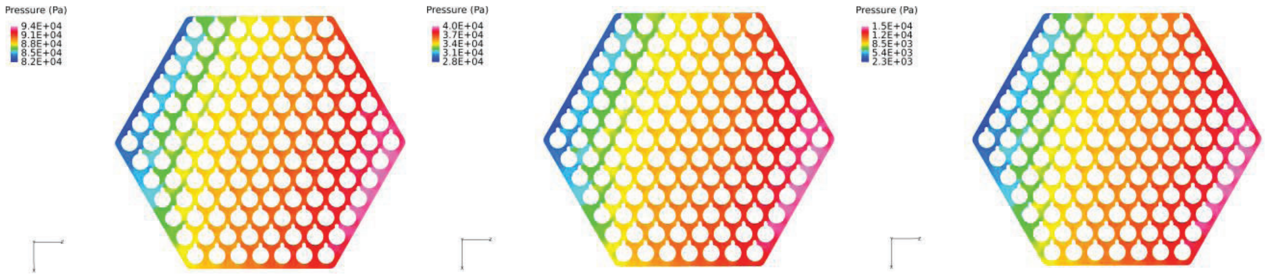


Figure 5. Transverse pressure distribution at different axial heights (from left to right): 1.75·H, 3.75·H, 4.75·H

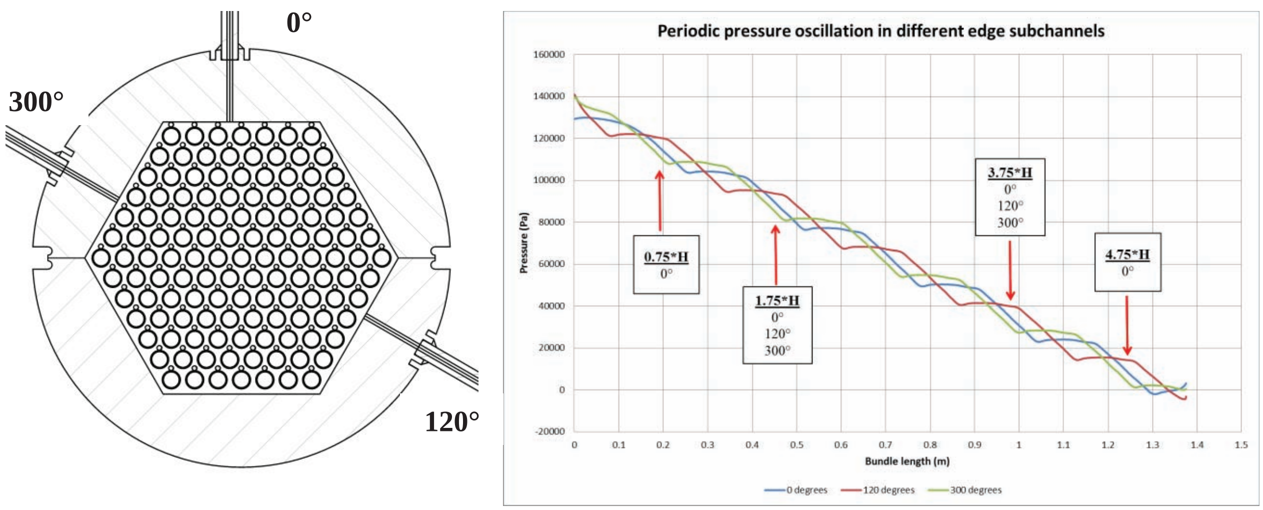
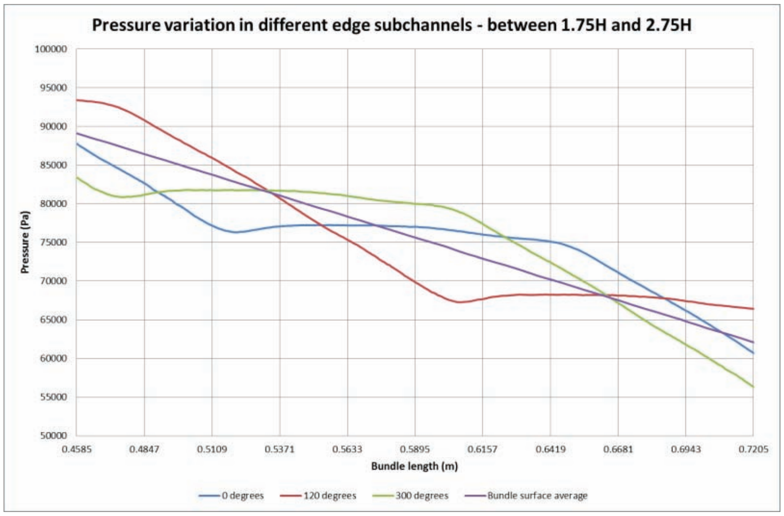


Figure 6. COMPLOT fuel assembly test section at an axial height of 3.75·H (left) and the corresponding axial pressure evolution per subchannel (right)

The choice of the edge subchannels at the azimuthal positions of 0°, 120°, and 300° respectively, was based simply on the transverse pressure distribution shown in Figure 5. The 120° and 300° positions correspond to a local maximum and minimum pressure respectively, while the 0° position is a tapping on an alternative face of the test section, which is more representative of the average pressure in the bundle.

Most importantly, the pre-test CFD results show the importance of the pressure tapping relative axial placement. Axial spacing of the pressure tappings in multiples of the wire-wrapper pitch, indicates that one can expect to measure a pressure drop, in each edge subchannel, that is representative of the bundle average pressure drop, and is repeatable for different subchannels. This is illustrated in Figure 7 when comparing the CFD surface averaged pressure drop to the pressure drop in each of the edge subchannels of interest, between the axial height of 1.75·H and 2.75·H.

Therefore, a total of eight pressure tappings are located along the periphery of the fuel bundle assembly. Their axial and azimuthal positions are shown in Figure 6, by the corresponding boxes in the pressure plot.



Subchannel	$\Delta P_{1.75H\text{-}2.75H}$ (mbar)
0°	270
120°	270
300°	271
Bundle surface average	270

Figure 7. Comparison of the CFD bundle surface averaged pressure drop, to the pressure drop in each edge subchannel, for one wire-wrap pitch (H)

3. EXPERIMENTAL RESULTS

The primary aim of this experimental effort is to determine the MYRRHA fuel assembly total pressure drop, while comparing the bundle pressure drop characteristics with existing friction factor correlations and CFD results. Therefore, the experimental matrix considers measuring the total pressure drop, and the fuel bundle specific pressure drop for various LBE flow rates. For this paper, however, only the bundle friction factor results are presented.

The steady state experiments were performed at a constant temperature of 200°C. A temperature of 200°C was chosen since this is the first experimental campaign with the COMPLOT facility. Further tests at higher temperatures will be performed in the future, to determine the influence of temperature. The raw data variables such as LBE volumetric flow rate, differential pressure, and LBE fluid temperature, each consider an experimental uncertainty that is derived from the statistical uncertainty associated with the time-averaging of the signals, combined with the uncertainty associated with the instrumentation and data acquisition.

Figure 8 illustrates a plot of the measured bundle pressure drops over one wire pitch as a function of the bundle Reynolds number, for each of the edge subchannels studied. This implies that the measured pressure drops between the axial heights of 1.75·H and 3.75·H were divided by two, and the measured pressure drops between the axial heights of 1.75·H and 4.75·H were divided by three, resulting in an averaged pressure drop over one wire pitch. The experimental results in Figure 8 show that for a given flow rate, the average pressure drop over one wire pitch between the axial height of 1.75·H and 3.75·H is the same for all three of the edge subchannels considered (0°, 120°, 300°). For higher turbulent flow rates the average pressure drop per wire pitch, measured across three wire pitches between the axial height of 1.75·H and 4.75·H, is the same as the average pressure drop per wire pitch measured across two wire pitches; however, at lower flow rates in the transitional flow regime, the pressure measurements across three wire pitches are in the order of 3-7 % lower, while for the lowest flow case of Re_{bdl} = 4200 the pressure drop is 22% lower.

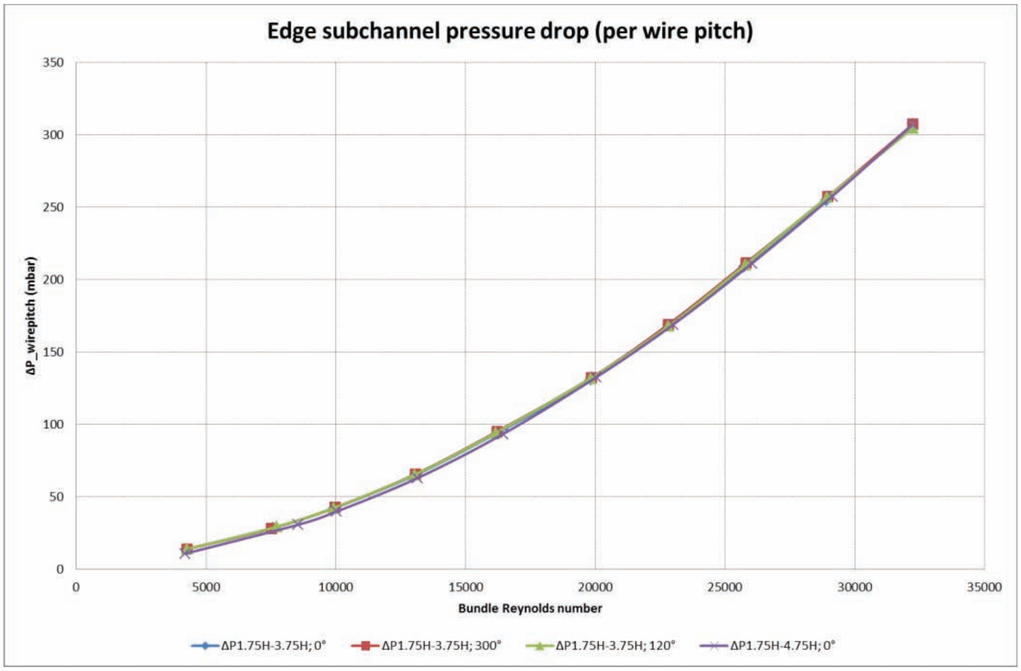


Figure 8. Edge subchannel pressure drop per wire pitch

The measured pressure drops were used to determine a friction factor (f) from the following well-known equation, for each corresponding flow rate:

$$\Delta P_{wirepitch} = f \cdot \frac{H}{D_{h,bdl}} \cdot \frac{\rho V_{bdl}^{\;2}}{2} \qquad (1)$$

where $\Delta P_{wirepitch}$ is the measured average pressure drop per wire pitch, H is the axial length or one wire pitch lead length, $D_{h,bdl}$ is the hydraulic diameter of the bundle, ρ is the LBE density, and V_{bdl} is the mean velocity in the bundle. Table II presents the measured friction factors, calculated using Equation 1, as a function of the bundle mean Reynolds number. Note that the bundle Reynolds number is calculated in terms of the bundle hydraulic diameter, $D_{h,bdl}$. All the physical properties of LBE used in calculations, are taken from [8].

Table II. Experimental friction factors – determined from the COMPLOT measurements

Mass flow rate (kg/s)	Re_{bdl} x 10^3	Between 1.75H-4.75H; 0°		Between 1.75H-3.75H; 120°	
		$\Delta P_{wirepitch}$ (mbar)	f x 10^{-3}	$\Delta P_{wirepitch}$ (mbar)	f x 10^{-3}
9,36 ± 0,20	4,20 ± 0,09	10,76 ± 0,35	50,98 ± 1,96	13,77 ± 0,06	65,23 ± 1,39
19,03 ± 0,21	8,53 ± 0,09	30,69 ± 0,58	35,15 ± 0,76	33,27 ± 0,14	38,10 ± 0,44
22,34 ± 0,21	10,02 ± 0,09	39,77 ± 0,47	33,07 ± 0,50	42,36 ± 0,13	35,22 ± 0,35
29,31 ± 0,22	13,14 ± 0,10	62,90 ± 0,68	30,39 ± 0,40	65,59 ± 0,23	31,69 ± 0,26
36,68 ± 0,23	16,44 ± 0,10	93,36 ± 0,89	28,79 ± 0,33	95,95 ± 0,36	29,59 ± 0,21
44,70 ± 0,24	20,03 ± 0,11	132,60 ± 1,14	27,53 ± 0,28	134,88 ± 0,42	28,01 ± 0,17
51,30 ± 0,26	23,00 ± 0,12	169,00 ± 1,62	26,65 ± 0,29	170,37 ± 0,78	26,86 ± 0,18
58,02 ± 0,24	26,04 ± 0,11	211,21 ± 1,87	26,03 ± 0,25	212,60 ± 0,59	26,20 ± 0,13
64,90 ± 0,25	29,13 ± 0,11	257,60 ± 2,07	25,37 ± 0,23	258,27 ± 0,88	25,44 ± 0,13
71,73 ± 0,27	32,23 ± 0,12	307,11 ± 2,54	24,76 ± 0,23	307,20 ± 1,03	24,77 ± 0,12

The measured friction factors presented in Table II, are plotted in Figure 9 as a function of the mean bundle Reynolds number. For reference, the wire-wrapped bundle flow regime boundaries proposed by Cheng and Todreas [9] are used to define the laminar to transition (Re_L) and the transition to turbulent (Re_T) Reynolds numbers respectively. These transition boundaries depend on the P/D of the bundle [9] and for the MYRRHA bundle these transitions are at Re_L = 906 and Re_T = 15 765. Figure 9 shows that in the turbulent regime, particularly for Re_{bdl} > 20 000, the experimentally determined friction factors are almost identical for the two measurements across different axial lengths. However, within the transition flow regime (Re_{bdl} < 15 765) the measured friction factors diverge and the friction factor across two wire pitches is 4-23% greater than the friction factor measured across three wire pitches.

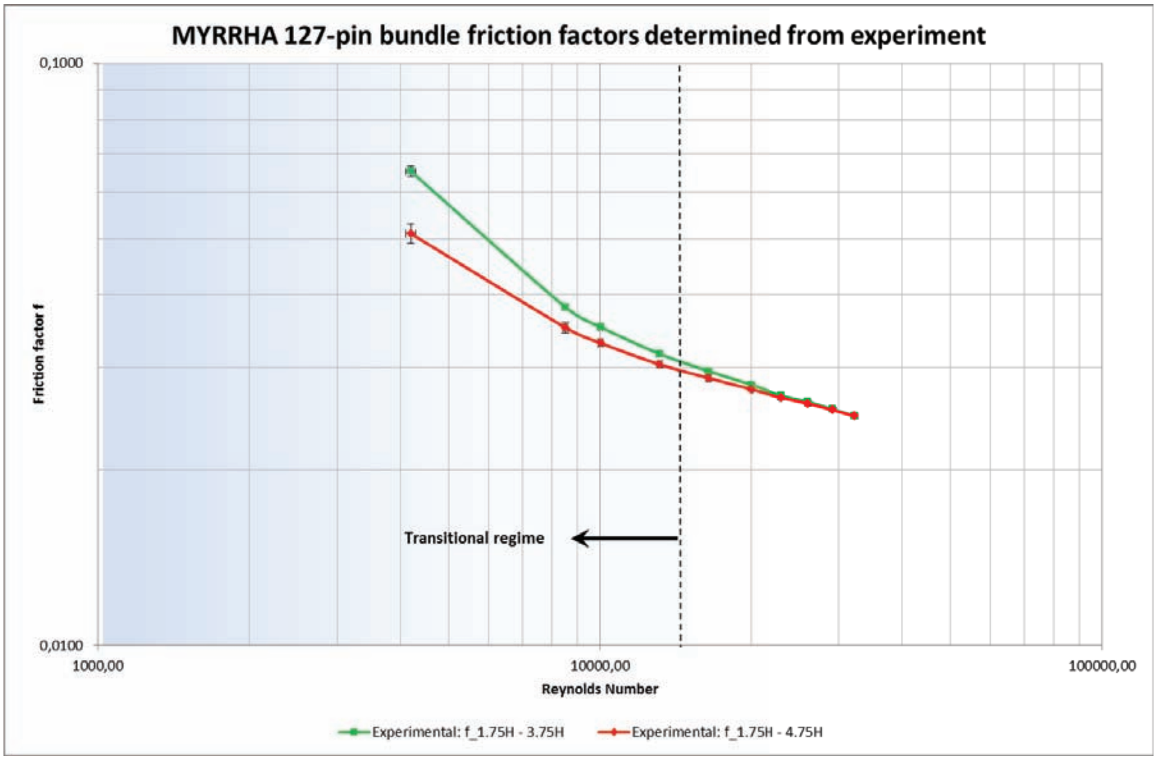


Figure 9. MYRRHA 127-pin bundle friction factors determined from experiment

Both sets of data in Figure 9 show the expected linear relationship between the friction factor and Reynolds number in the turbulent regime (Re_{bdl} > 15 765). Below the transitional boundary Reynolds number, this relationship changes with an increase in the slope at a definitive kink in the data curve at Re_{bdl} ≈ 9000 – 10 000. The differences between the two data sets are believed to be due to the flow development within the bundle.

3.1. Comparison with correlations and CFD

The experimental pressure drop and friction factors are compared against numerous existing friction factor correlations and plotted against the mean bundle Reynolds number in Figure 10. The correlations selected for comparison in Figure 10, are those correlations recommended by Chen and Todreas [4] for their good agreement with experimental data from wire-wrapped fuel bundle assemblies. These include the correlations by Rehme [10], Cheng and Todreas [9] (both the simplified (CTS) and detailed correlations (CTD)), and Baxi and Dalle Donne (BDD) [11].

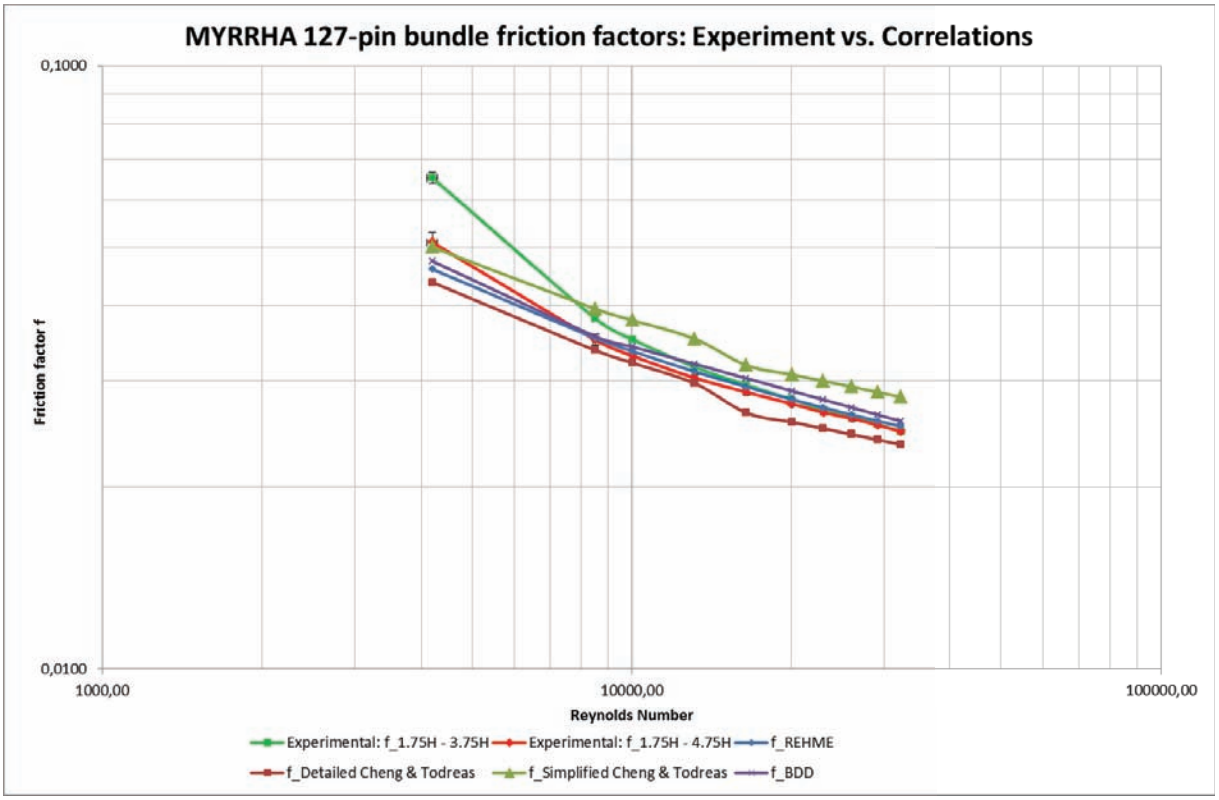


Figure 10. Comparison of experimental bundle friction factors versus existing correlations

The comparison with existing correlations shows that the correlation by Rehme [10] represents the MYRRHA bundle friction factor the most accurately. Table III shows that the Rehme correlation over predicts the friction factor consistently by ~1-2%, except for the lowest flow case (Re = 4200) where the friction factor is under predicted by almost 10%. The simplified Cheng and Todreas [9] (CTS) model and the Baxi and Dalle Donne (BDD) [11] model show the closest agreement at the lowest flow case with an under prediction of ~2% and ~7% respectively. Further testing with more data points at low flow rates is necessary to determine the bundle hydraulic behaviour and performance of these correlations near the laminar flow regime.

Table III. Prediction error by existing bundle friction factor correlations

Re_{bdl} x 10^3	% error (Rehme)	% error (CTD)	% error (CTS)	% error (BDD)
4,20	-9,70	-14,11	-1,82	-6,93
8,53	0,62	-3,94	12,52	1,29
10,02	1,76	-2,65	14,55	3,54
13,14	2,46	-2,06	16,10	5,46
16,44	2,00	-7,59	10,80	5,40
20,03	1,67	-6,75	11,81	5,04
23,00	1,80	-6,00	12,70	4,96
26,04	1,42	-5,90	12,83	4,27
29,13	1,61	-5,38	13,45	4,10
32,23	1,99	-4,78	14,17	4,10

The experimental results for the MYRRHA nominal mass flow rate case of 71.4 kg/s are compared with the results from the CFD analysis by NRG and the differences are tabulated in Table IV. Note that the experimental values were determined with a mass flow rate of 71.73 kg/s, slightly higher than the nominal case of 71.4 kg/s. The CFD model predicts an average pressure drop over one wire pitch and a corresponding friction factor that is ~12% lower than the experimentally determined values, for the measurements across two wire pitches. This difference is ~13.5% across three wire pitches. Interestingly the CFD model predicts a lower average wire-wrapper pressure drop across the three wire pitches, a trend that was also seen in the experiments but which was only evident at lower flow rates in absolute pressure terms.

Table IV. Comparison between experimental and CFD results for the MYRRHA nominal flow rate

Variable	Experiment	CFD	% difference
$\Delta P_{wirepitch}$ 1.75H-3.75H (mbar)	307,20 ± 1,03	270,05	-12,09
$\Delta P_{wirepitch}$ 1.75H-4.75H (mbar)	307,11 ± 2,54	265,53	-13,54
$f_{1.75\text{-}3.75}$ (x10^{-3})	24,77 ± 0,12	21,79	-12,05
$f_{1.75\text{-}4.75}$ (x10^{-3})	24,76 ± 0,23	21,42	-13,49

4. CONCLUSIONS

To support the design and licensing of the MYRRHA reactor, the large-scale COMPLOT LBE facility at SCK•CEN has been used to test the hydraulic characteristics of a full-scale fuel assembly mockup, at various LBE flow rates. The COMPLOT vertical test section is representative of a single MYRRHA core position or in-pile section (IPS) at full height, with the LBE flowing upwards like in MYRRHA.

The COMPLOT FA test section itself has been constructed from a specially designed thick-walled hexagonal tube, to represent only the inner profile and associated hydraulics of the MYRRHA FA, which is filled with 127 wire-wrapped fuel pins. The fuel assembly test section has been strategically instrumented with numerous pressure tappings, in order to measure the total fuel assembly pressure drop, as well as the fuel assembly bundle pressure drop characteristics, in specific edge subchannels.

The fuel assembly bundle isothermal pressure drop experiments show repeatable friction factor measurements at a temperature of 200°C, with an uncertainty of less than 1%. The experimental results show that the correlation by Rehme [10] represents the MYRRHA bundle friction factor the most accurately. Rehme's correlation over predicts the friction factor consistently by ~1-2%, except for the lowest flow case (Re_{bdl} = 4200) where the friction factor is under predicted by almost 10%. The simplified Cheng and Todreas [9] (CTS) model and the Baxi and Dalle Donne (BDD) [11] model show the closest agreement at the lowest flow case (Re_{bdl} = 4200) with an under prediction of ~2% and ~7% respectively. Further testing with more data points at low flow rates is necessary to determine the bundle hydraulic behaviour and accuracy of these correlations near the laminar flow regime.

The comparison between the experimental and the CFD results at the MYRRHA nominal flow rate, reveals that the CFD model under predicts the bundle friction factor by ~12-13.5%. Indeed the CFD model includes a heated bundle which will influence the comparison due to the difference in the average bundle temperature. Further experimental tests will be performed to determine and quantify the influence of temperature on the friction factors.

NOMENCLATURE

$D_{h,bdl}$	bundle hydraulic diameter (m)
$\Delta P_{wirepitch}$	average frictional pressure drop for one wire pitch (Pa)
f	friction factor
H	wire-wrapper pitch (m)
Q	volumetric flow rate (m^3/h)
Re_{bdl}	bundle mean Reynolds number
Re_L	laminar to transition boundary Reynolds number
Re_T	transition to turbulent boundary Reynolds number
ρ	fluid density (kg/m^3)
V_{bdl}	bundle mean fluid velocity (m/s)

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