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Development of a measurement technique for detailed flow characterization in fuel bundles

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ABSTRACT

Investigating the flow behavior in fuel rod bundles has been an active research topic since many decades. Nowadays, despite the great advances in computational fluid dynamic techniques and resources, blind benchmarks have shown numerical results are still very dependent on schemes and closure models. Moreover, most experimental studies in flow mixing and flow structure identification were performed in simplified geometries and/or in a very limited test domain. In addition, reliable experimental data from mixing experiments in the vicinity of a spacer grid in rod bundles are almost non-existent, especially with high spatial and temporal resolution.

Generating experimental data relevant for fuel bundle geometries is costly and generally limited to a small measurement region. In this work a novel non-intrusive technique is developed and tested in order to characterize the flow in a geometry resembling a fuel bundle by using of detailed pressure measurements. The measurement device makes use of electronic micromachined deformable membrane differential pressure sensors with fast dynamical response, allowing capturing local pressure fluctuations. Such differential pressure sensors are connected to a fix pressure tap and a movable pressure tap drilled in each of the rods. Each instrumented rod is free to move both axially and azimuthally allowing scanning the static pressure drop values at the surface of the rod. In addition, by analyzing the static pressure fluctuations it is possible to capture valuable information of turbulence phenomenon such as the turbulence kinetic intensity and the turbulence power spectrum in a wide spatial range, including regions within spacer grids.

1. Introduction

Nuclear power plants are capable of producing a very high power density. In particular, the produced power is mainly limited by the core cooling mechanism and the susceptibility to instabilities (Marcel et al., 2017b; Marcel et al., 2013), which must assure the mechanical integrity of the fuel bundles. The so-called critical heat flux (CHF) is a thermal-hydraulic phenomenon that limits the heat extraction capacity of the water-based cooling systems, abruptly degrading the heat transfer mechanism between the fuel rods and the coolant (Becker et al., 1964). CHF should be avoided in all operating conditions since their occurrence can compromise the integrity of the reactor core. This phenomenon is closely related to the local thermal-hydraulic conditions of the coolant in the fuel assemblies. If we succeed in changing these conditions, improving the local cooling capabilities, the produced power could be increased while maintaining the required safety margins. The optimization of the fuel bundles design can increase the energy production capacity of current and future nuclear power plants (Yi et al., 2013).

The idea behind optimizing the fuel bundle design from the thermal-hydraulic point of view is not something new, but historically pursued. So far, most attempts to improve cooling conditions have been based on indirect observations of the phenomena involved. The methodology proposed in this work will provide quantitative data to identify the geometrical locations where it would be reasonable to intervene to improve the local cooling conditions.

For many decades, improvements of heat transfer performance through passive and active methods have been studied intensively. Typical examples of passive methodologies are surface roughness, flow deviators and vortex generators (Groeneveld, 2008). Ribs, indentations, spiral flutes, and coil inserts are some common surface modification techniques that are effective for many applications (Huang, 2012), and can be used conveniently for existing fuel bundles (Chang et al., 2003). Nowadays, the use of nanostructured surfaces for heat transfer

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Nomenclature

Normal alphabet

D	diameter (m)
D_h	hydraulic diameter (m)
f	frequency (Hz)
f_d	friction factor
f_p	vortex passage frequency (Hz)
P	pitch (m)
S	gap (m)
$\bar{v}$	mean velocity (m/s)
v^*	friction velocity (m/s) $\left(v^* = \bar{v}\sqrt{\frac{f_d}{8}}\right)$

Greek

ρ	liquid density (kg m^{-3})
τ_w	wall shear stress (N m^{-2})

Abbreviations

DAQ-OS	digital acquisition system – operative system

Dimensionless numbers

Re_D	Reynolds number $Re_D \equiv \frac{\rho VD}{\mu}$
Str	Strouhal number $Str \equiv \frac{f_p D}{v^*}$

enhancement is an active field of work for many applications, including nuclear industry (Marcel et al., 2017a). Active methods, which have also been extensively studied, require the addition of external power to produce the desired flow modification. Examples of this type include heat transfer surface vibration, fluid vibration, and electrostatic field introduction, which are costly and complex and therefore not suitable for nuclear fuel bundles (Masson and Carrica, 1999).

Improving heat transfer performance requires a thoroughly knowledge of the flow inside complex geometries such as nuclear fuel bundles. Traditional flow measurement techniques such as Laser Doppler Anemometry (LDA) or Particle Image Velocimetry (PIV) are complex and very expensive which considerably limit its use in complex geometries as those studied in this work (Goldstein, 1996; Swales et al., 1996). In addition, since these techniques require an optical access to the measurement domain, they are practically impossible to use them in inner subchannels defined *inside* spacer grids. As it will be shown in the following sections, the technique presented here is relatively inexpensive, easy to calibrate, robust and provides valuable information which is potentially useful for determining mixing in fuel bundles.

The Thermal-hydraulics Department from the Bariloche Atomic Center has designed and constructed a testing facility for 3D pressure mapping in complex geometries (Nalín, 2016). The aim of this facility is to develop and prove a novel technique able to collect enough information for both, investigations of flow structures in fuel bundles and numerical code benchmarking tests. Understanding the flow dynamics in complex geometries can help identifying deficient cooling points in the fuel bundle, including regions close and within spacer grids. Different mixing devices can thus be inserted in the neighborhood of those points in order to promote local mixing (such as turbulence promoters, flow diverters, appendages, etc.). In addition, by studying the mixing capabilities of the different proposed devices will help in developing an optimized version of the fuel bundle. This supplementary tool is intended to play a very important role in the optimization process since it will enormously reduce the time and costs by limiting the number of fuel bundle designs to test in the CHF experimental facility present in the Laboratory. As mentioned above, this optimization can increase the power at which CHF occurs, and therefore the operating reactor power.

In this work we introduce a novel measurement technique able to providing high quality data for a detailed hydraulic characterization of fuel bundles. In addition, by analyzing fluctuations in the static pressure signal, it is possible to capture valuable information of turbulence phenomenon such as the turbulence kinetic intensity and the turbulence power spectrum in a wide spatial range. Such characterization will support the optimization and design process of fuel bundles concerning thermal-hydraulic aspects, providing a tool for nuclear plants to better exploit its potential.

2. Phenomenology involved

This section discusses the physical mechanisms that contribute to the flow structure in complex geometries. Nuclear fuel assemblies are commonly arranged in square or triangular-latticed parallel aligned rod bundle geometries. In this type of geometry, the flow area bounded by neighbor tubes defines a subchannel. Each subchannel connects to the adjacent ones by a gap between two rods. The pitch-to-diameter ratio (P/D) of a rod bundle defines the gap spacing S.

In addition to the major axial flow, there also may be present transverse interchange of mass, momentum and/or energy between two adjacent subchannels, through the gaps connecting them. The net transversal flow is known as cross-flow. Rogers and Todreas (1968)

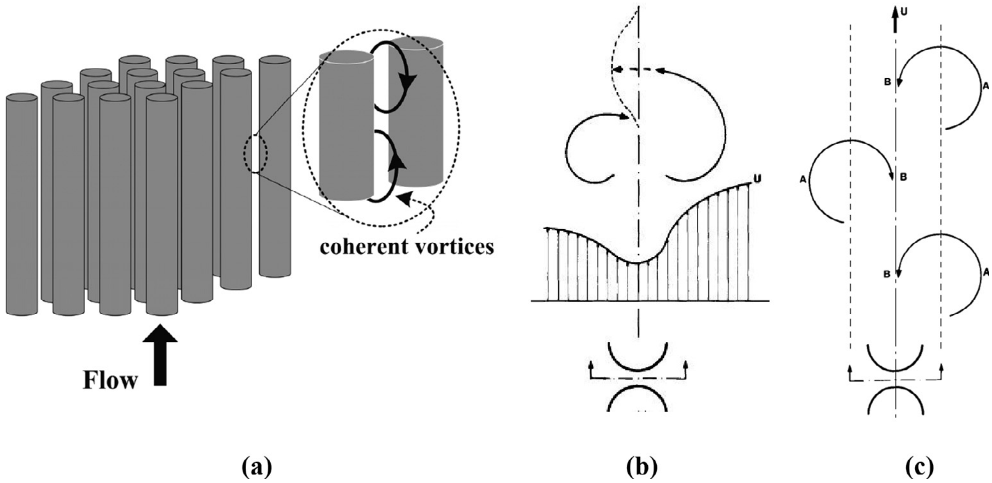


Fig. 1. Mechanism of large-scale coherent vortex street formation (Mahmood, 2011).

identified the following two mechanisms constituting the single-phase cross-flow in vertical rod bundle geometry and influencing the process of inter-subchannel cross-flow mixing:

2.1. Diversion cross-flow

Transversal pressure gradients existing within two adjacent subchannels, causes lateral flow and therefore a net mass interchange contributing to subchannel mixing in rod bundles. Lateral pressure differences can result from different subchannel hydraulic diameters, heat flux distributions and gradual or abrupt changes in flow areas caused, for example, by element bowing and tube supporting spacer grids, respectively.

2.2. Turbulent cross-flow

This is a result of stochastic flow and pressure fluctuations. Three transport mechanisms, in fully developed turbulent flow near gap regions have been identified: convection by mean motion, turbulent convection, and turbulent diffusion (Wu, 1995). The first mechanism represents secondary flows of Prandtl's second kind, generated by the non-uniformity of turbulent stresses. Turbulent convection and diffusion are associated with large-scale and small-scale eddies, respectively (Mahmood, 2011).

In 1973–1974, Rowe (1973), Rowe et al. (1974) based on their measurements were one of the first to indicate that macroscopic flow processes exist adjacent to the gap region in a square arrayed rod bundle. Furthermore, they found out that rod gap spacing (P/D) is the most significant geometric parameter affecting the flow structure.

Hooper and Rehme were the first to systematic investigate the existence of coherent structures in rod bundle geometry. First, in Rehme's 4-rod bundle, Hooper observed a strong auto- and spatial cross correlation of the axial and transverse velocity components in the rod gap (Hooper and Rehme, 1983; Hooper and Rehme, 1984).

In 1989 Möller (1989) proposed a flow model of a street of vortices moving in the center of the gap rotating alternately in opposite direction which tried to explain these findings. The axis of these vortices would be perpendicular to the rod surface in the gap and move in axial flow direction, see Fig. 1a).

The mechanism causing large-scale coherent vortices in fuel bundles can be explained as follows. Considering turbulent and developed flow between subchannels, we may think in a transversal velocity profile as indicated in Fig. 1b) in which the velocity profile and the vorticity are different in each side of the gap. Under these conditions, two vortices are generated one in each side of the gap. Since no wall at the center of the gap obstructs the motion of vortices, large-scale vortices can stabilize and cross the gap while they are transported by the main flow, resulting in a vortex street like that shown in Fig. 1c).

These kinds of structures are known as large-scale coherent vortices. Many researchers support the idea they are the main contributor to the exchange of mass, momentum and energy in rod bundle geometries. Rogers and Tahir (1975), Moller (1992), Rehme (1992), Lexmond et al. (2005) and Guellouz and Tavoularis (1992) are few of those who had experimentally demonstrated and stressed the dominant role of these vortices in the cross-flow mixing, as proposed in Mahmood (2011).

The effect of large-scale coherent vortices in the cross-flow mixing in rod bundle geometry is rather a unique case. Since most of the above-mentioned studies were carried out for turbulent flows, many researchers had considered this phenomenon under the heading of turbulent cross-flow mixing. Although eddies of different scales do exist in turbulent flows, conventionally these eddies are seen as non-coherent in nature. In fact, this is also the reason behind the use of the terminology 'vortices' instead of 'eddies', since the latter is considered associated with conventional turbulence. Furthermore, owing to the existence of these large vortices in laminar and transitional flows also, it seems reasonable to add this as a new cross-flow mixing contributing phenomenon, in addition to the two mentioned above (Mahmood, 2011).

As a consequence of the Helmholtz's second theorem a vortex line or vortex tube must either be closed or start/end at solid boundaries. Let us consider now the presence of large scale coherent vortices in rod bundles. By recalling the Kelvin's circulation theorem for inviscid flows, it follows that vortex lines move with the fluid since circulation is conserved. The vortex line may become contorted but nevertheless it remains a vortex line. A natural extension of this argument shows that it must also be true for vortex tubes, i.e. if circulation is conserved, vortex tubes move with the fluid. From kinematic arguments the vortex tube strength remains fixed with time. If the vortex tube is stretched and its cross sectional area decreases (as would be the case if the fluid is nearly incompressible) the vorticity in the tube must increase to keep the vortex tube strength (or equivalently its circulation) fixed. Hence, vortex tube stretching can increase the vorticity when circulation is conserved. This might be the case of large-scale coherent vortices passing transversally from one subchannel to an adjacent one in rod bundles. In this case, the vortex tube would decrease-increase its vorticity and therefore its rotational velocity when passing through the gap. For this reason despite their main movement is essentially two-dimensional in rectangular gaps, large-scale coherent vortices may contain more three-dimensional characteristics in rod bundle flow.

Cross mixing allows homogenizing coolant temperature in nuclear fuel elements and mitigates the consequences of having a radial power profile. In fact many authors consider this as the most important of all in subchannel mixing phenomena (Meyer, 2010). For this reason it is of great importance to thoroughly investigate cross mixing in nuclear fuel bundles geometries.

In 2006 Baratto, Baratto et al. (2006) published results obtained in a section of a 37-rod bundle, see Fig. 2, to determine heat transfer characteristics. They found that coherent structures in adjacent gap regions are highly correlated and interfere with each other to the point that a change in frequency in one gap following a rod displacement imposes the same change to the frequency in the other gap. Contrary to their own earlier findings in Guellouz and Tavoularis (2000) they found the frequency of the pulsations to decrease with decreasing gap size. This may result from the specific test conditions applied (Meyer, 2010).

Currently there are many thermal-hydraulics codes aiming to calculate cross mixing provided the subchannel mixing coefficients are known (Jackson and Todreas, 1981; Carver et al., 1984; Battelle Pacific Northwest Laboratories, 1976). In other words, the accuracy of these codes depends on the correct use of mixing correlations and subchannel models and data. Due to this it is necessary to have very detailed measurements in spatial and frequency domains if we want to understand and propose mechanistic models able to capturing the correlation and interference phenomena of large-scale coherent vortices in nuclear fuel bundles subchannels.

In this work we show the capabilities of a system designed to measure the dynamics of differential pressure signals aiming to capturing the complex phenomenology existing in nuclear fuel bundles flows.

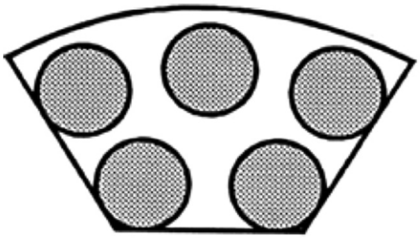


Fig. 2. Schematic view of the 37-rod bundle section used in Baratto et al. (2006) for identifying correlations and interferences between large-scale vortices in rod bundles.

3. Experimental method

The experimental facility, aimed for detailed pressure drop measurements, is shown schematically in Fig. 3. Since it is a preliminary version of the full scale circuit, it only simulates part of the complex geometry of a prototypical nuclear fuel bundle. The goal of this test loop is to demonstrate the feasibility of the proposed methodology. The system consists in an acrylic tube containing a group of 7 rods and spacer grids (SGs) equally spaced in the axial direction, mimicking a portion of a fuel bundle. The working fluid is water at atmospheric pressure, which is driven through the test section by a centrifugal pump to a tank located at the top. The fluid then returns through the downcomer section which closes the loop. An orifice plate and a turbine flowmeter are used for determining the flow rate. The actuation of a valve, located at the exit of the pump, allows varying the mass flow rate. The instrumented rods and the acrylic tube have static pressure taps for measuring the differential pressure, similar to those used in Caraghiaur et al. (2004), see Fig. 4. Each pressure tap consist of a 0.3 mm drilled hole which represents a 2.7° arch of the rod circumference. The pressure taps are connected from the inside of the rod with plastic tubes to a set of differential pressure sensors. The flexible

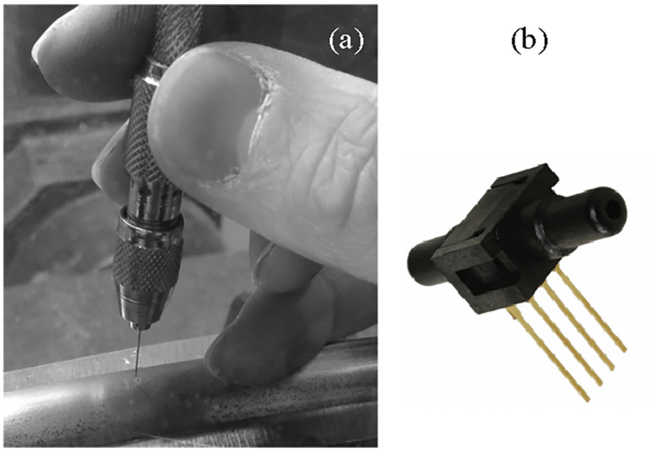


Fig. 4. a) Detail of the 0.3 mm pressure tap drilled on an instrumented rod for static pressure measurements. b) Picture of the micromachined deformable pressure drop sensors used in this work.

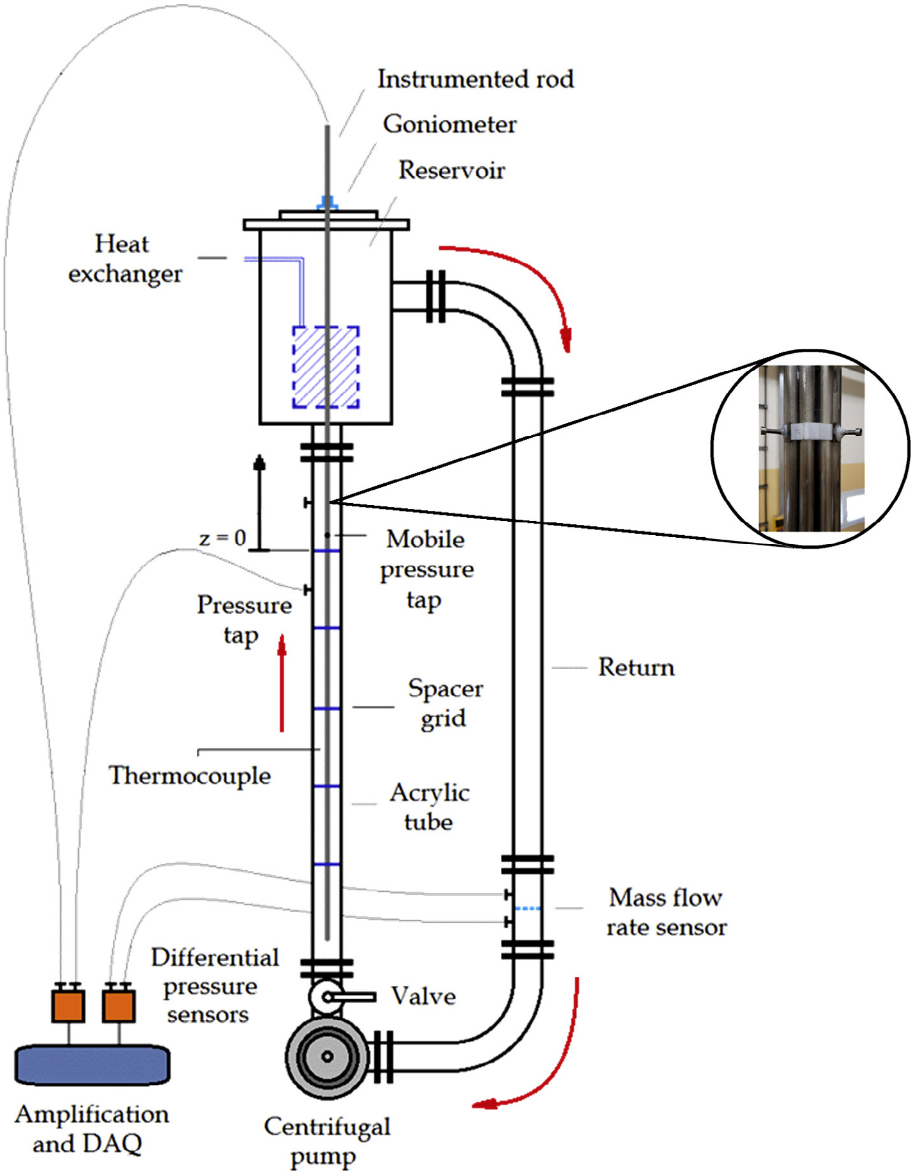


Fig. 3. Schematic view of the test facility. For simplicity the positioning system of the instrumented rods is not included.

plastic tubes are translucent to ensure proper purging of air bubbles prior to testing. The differential pressure sensors are electronic micromachined deformable membrane sensors which are able capturing fluctuations of the stating pressure within a broad range of frequencies (Honewell 24PCB). The instrumented rods are free to move both axially and azimuthally thus positioning the corresponding pressure tap at any desired location. In this manner it is possible to scan the static pressure drop at the surface of the rods. An automatic positioning system has been implemented at the top of the test section allowing controlling the angular and azimuthal displacement of the instrumented rods. Such a system is not included in Fig. 3 for simplicity. A heat exchanger located in the upper tank is used for maintaining a constant coolant temperature, i.e. it is used for compensating the fluid heating due to viscous dissipation.

For the measurement process, the tap of the rod must be set at the point of interest, and the data acquisition can be done with the system running at steady state conditions (regarding the mass flow rate and temperature). The process is repeated for every point of interest until the desired spatial resolution is achieved. In the case of a nuclear fuel bundle, due to the large number of rods that will be instrumented, the pressure drop in the three dimensions could be reconstructed with reasonable uncertainty, allowing capturing important information for flow characterization including subchannel mixing and associated turbulence.

Spacer grids support the rods and maintain proper geometrical configuration of fuel rods within the fuel bundle and have the important bi-function of enhancing the lateral exchange of flow momentum and energy (Lahey and Moody, 1993). They reduce the fuel assembly flow area by contracting the flow and then expanding it downstream of the spacer grid. The flow area blockage creates additional turbulence, flow separation and mixing. Thus, the flow and thermal boundary layers are disrupted and reestablished by the spacer grid. This effect tends to enhance the local heat transfer within and downstream of the spacer grid (Stosic, 1999). Thus areas near the spacer grids are particularly interesting, homogenizing the subchannels temperatures in the fuel bundle. On top of this, a spacer grid represents a significant part of the total pressure drop in the core. In this way, designing a spacer grid is a tradeoff between various optimization goals. As mentioned by many authors, detailed experimental data are needed to develop and validate computational models able to predict the flow around and within spacer regions (Lahey and Moody, 1993).

In the present work, dedicated spacer grids made of Teflon™ (PTFE) are used in order to facilitate sliding and rotation of the instrumented rods. Fig. 5 shows pictures of the spacer grids and the way they are positioned within the test tube.

Seven instrumented rods are held in position by six Teflon™ spacers such that shown in Fig. 5. The rods could slightly vibrate. The walls of the test section are made of a 4 mm thick acrylic tube, allowing optical techniques to be used to study the flow. The characteristic geometric parameters of the test section are given in Table 1.

Table 1
Characteristic geometric parameters of the test section.

Rod diameter	12.7 mm
P/D (pith-to-diameter ratio)	1.22
Rod length	2000 mm
Cross-sectional flow area	1049 mm^2
Hydraulic diameter	9.52 mm
Loop pressure	1 atm.
Loop temperature	20 °C

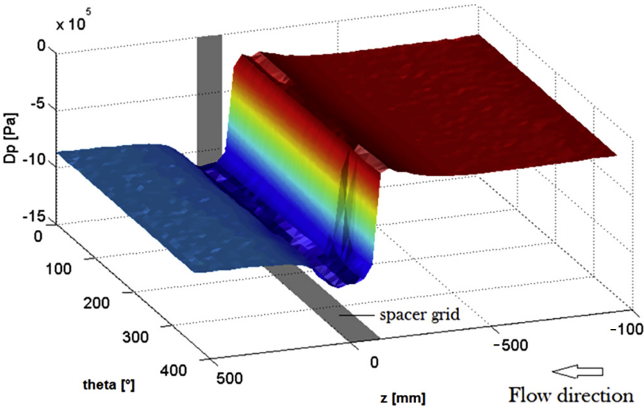


Fig. 6. 3-Dimensional reconstruction of the time average static pressure measured on the surface of the central rod. Note the clear influence of the spacer grid in the pressure drop evolution over the flow direction.

To avoid as much as possible effects the measurements are performed over spacers five and six. In addition, the circulating pump is mechanically isolated from the rest of the loop by using rubber hoses. In this way mechanical vibrations which affect the pressure fluctuations are reduced.

The present technique has a maximum resolution of 2.7° and 1 mm in azimuthal and axial directions respectively. In addition the sensors have a 0.005psi (∼35 Pa) uncertainty in pressure and a time response smaller than 1 ms, allowing capturing most turbulent related phenomena.

4. Results

In this section, different results are shown aimed to demonstrate the capabilities of the present measurement technique. For this purpose, the facility was operated producing a turbulent flow characterized by a Reynolds number, $Re_{Dh} = 30250$. The Re is based on the bundle hydraulic diameter and bulk velocity.

Fig. 6 shows the time average differential static pressure recorded with the central instrumented rod. As can be observed the pressure

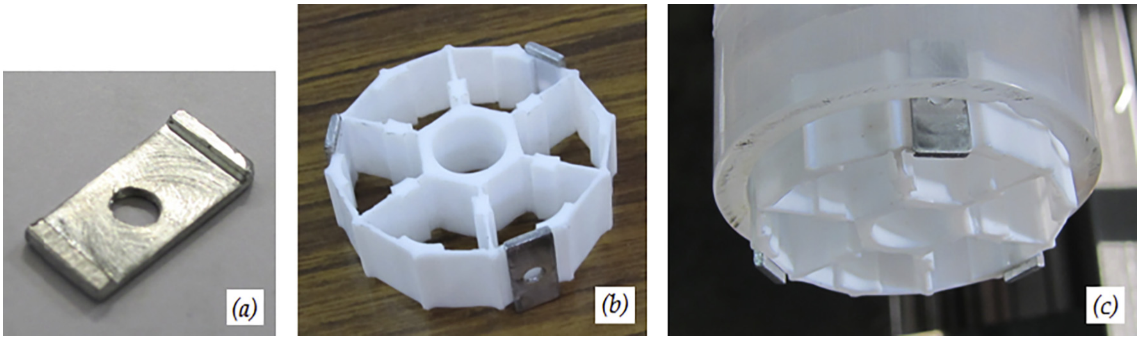


Fig. 5. Spacer grid used in this work: a) Spacer grid positioning device. b) Teflon™ spacer grid with positioning devices. c) Mounting the spacer grid within the test tube.

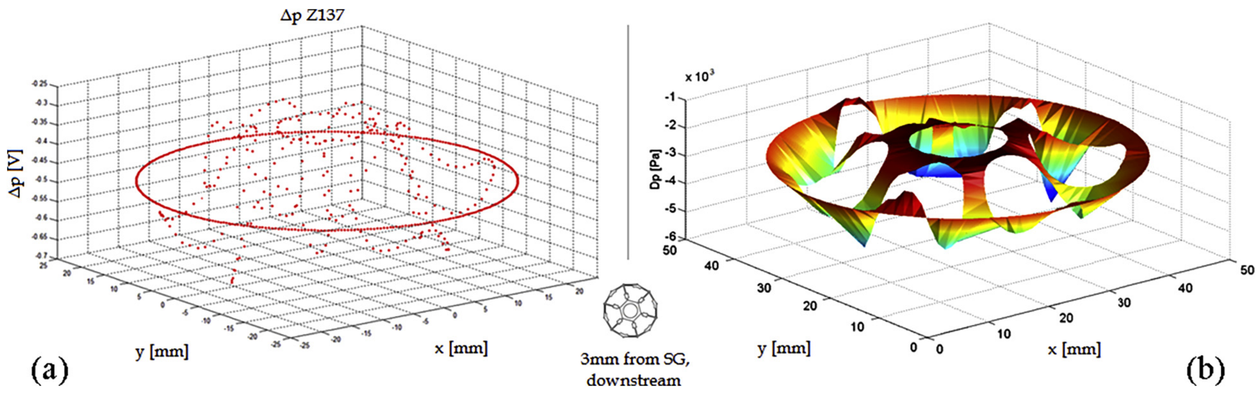


Fig. 7. a) Time average static pressure measured on all the instrumented rods when all the pressure taps are located 3 mm upstream the spacer grid. b) 3-dimensional reconstruction of the static pressure within the cross sectional area.

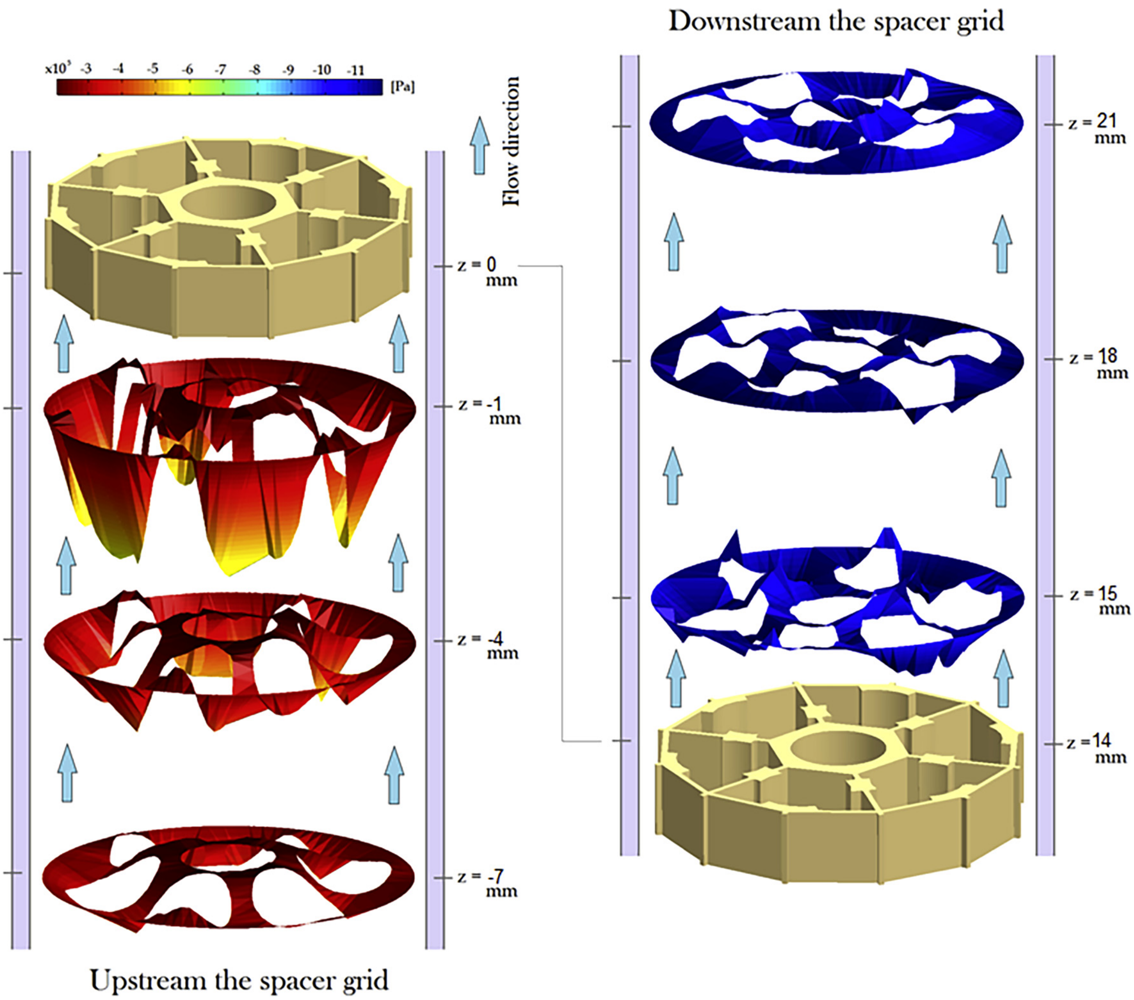


Fig. 8. Axial evolution of the three-dimensional reconstruction of the static pressure within the cross sectional area.

drastically reduces when the flow passes through the spacer grid. In addition, the pressure recovery length is clearly visible.

When using the time averaged static pressure measurements recorded by all the instrumented rods at a certain axial position (see e.g. Fig. 7a)) a three-dimensional reconstruction of the static pressure can be performed, such that presented in Fig. 7b). It needs to be emphasized that despite the questionable interpolation done in this type of reconstruction, valuable information can be drawn from this representation. For instance, a high pressure value of static pressure can be related with local low velocities (such as those encountered in the vicinity of the central rod in Fig. 7). In contrast, low values of static pressure are associated with local high velocities (such as those encountered in the outer subchannels, see Fig. 7). The high quality of the measured data allows us identifying the region where the rod is in contact with the spacer grid.

By performing a number of iso-axial position 3-dimensional reconstructions of the time average pressure drop measurements it is possible to determine the trend of the flow characteristics when passing through a spacer grid. An example of this type of plot can be observed in Fig. 8. The static pressure reconstruction upstream shows a well-

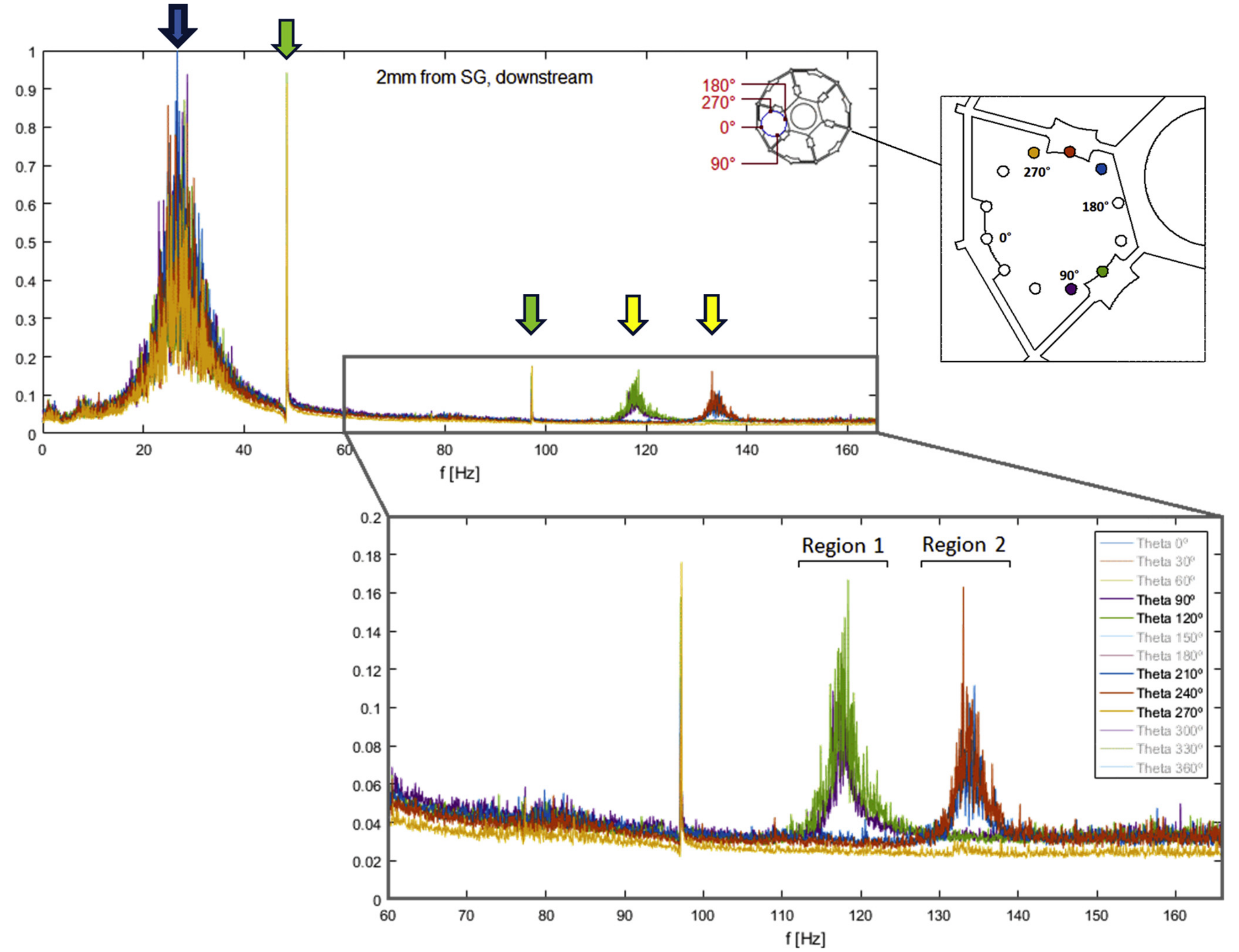


Fig. 9. FFT of selected pressure drop signals in the vicinity of a spacer grid, downstream. The blue arrow indicates the region of large-scale coherent vortices and mechanical natural resonance frequencies; the green arrows show the frequencies corresponding to flow pulsations induced by the circulating pump; the yellow arrows show frequencies associated to hydro-dynamic phenomena. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

structured pattern with clear transversal static pressure gradients which are related to the mechanism of flow diversion. Once the flow has passed the spacer grid, the change in geometry promotes lateral mixing enhancing pressure homogenization, resulting in much lower transversal static pressure gradients.

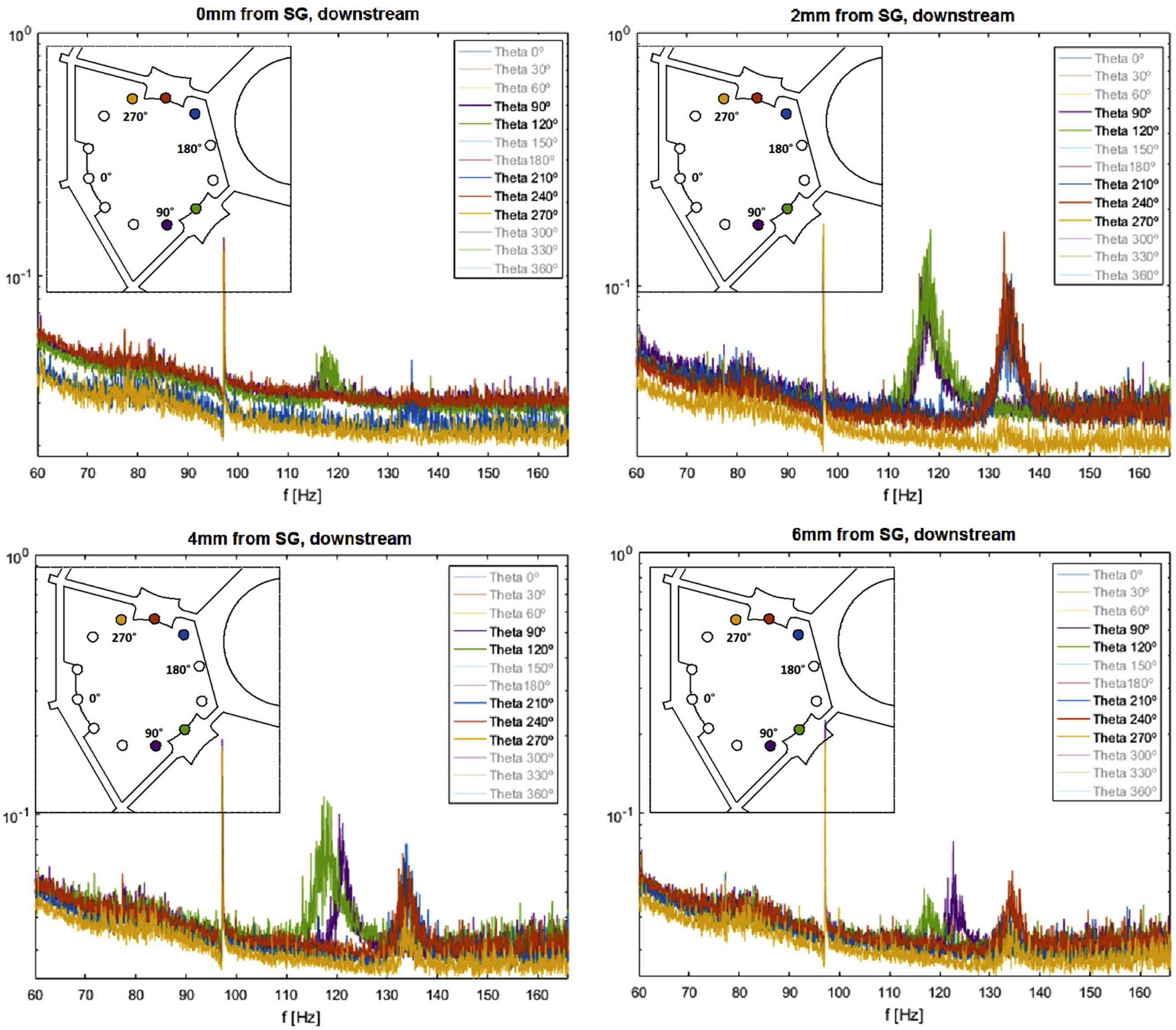
In order to exploit the potential of the measurement technique developed and presented in this article, the dynamical analysis of the pressure drop signals is performed. One of the most widely used tools for decomposing regular fluctuations is the Fast Fourier Transform (FFT) of a signal. Different physical mechanisms can thus be identified and its effect quantified with this type of analysis.

The experimental setup, allows acquiring static pressure fluctuations for each pressure tap location and for each instrumented rod. In this way, by analyzing the frequency spectrum of all the available signals we can identify and quantify the characteristics of the flow in a 3-dimensional way. In particular it is possible to investigate the evolution in space of important phenomena in fuel bundle design like turbulence intensity, subchannel mixing, flow diversion, existence of coherent structures, etc.

At this point it is important to recall that the pressure drop measuring setup is able to capturing phenomena with characteristic frequency below 166 Hz. In our case the limiting component is the DAQ-OS. This constrain, which limits capturing high frequency phenomena associated to turbulence, is being solved for future versions of the actual experimental setup.

When analyzing a noisy signal, however, one should be able to discriminate different typical frequencies in the spectrum in order to associate them to physical mechanisms, some of which are not relevant for the flow characterization process. Particularly, it is necessary to discriminate mechanical and pump-induced frequencies from hydrodynamic relevant phenomena. By analyzing the number of vanes in the impeller of the pump and also the RPM of the motor, it could be determined the typical frequencies associated to flow pulsations originated by the circulating pump. These are $f_1 = 48$ Hz and $2f_1 = f_2 = 96$ Hz, which are clearly visible, see Fig. 9. This finding was afterwards confirmed with the invariant nature of these frequencies with the mass flow rate regulated with a valve. It needs to be emphasized the signal associated to Fig. 9 corresponds to a tap located in a peripheral rod 2 mm downstream of the spacer grid.

Based on the bibliography, it is found that the dynamics of large-scale coherent vortices is characterized by regular phenomena associated with some characteristic frequencies (Hooper and Rehme, 1984; Möller, 1991; Houssain, 1983). In particular, the vortex passage frequency is the most important one since this phenomenon seems to dominate the flow dynamics. An estimation of this frequency can be obtained using Eq. (1) based on the Strouhal number (Wu and Trupp,



0mm from SG, downstream

2mm from SG, downstream

4mm from SG, downstream

6mm from SG, downstream

Fig. 10. FFT of selected pressure drop signals in the vicinity of a spacer grid, for different angular and axial locations downstream. The decay of the hydrodynamic induced frequency activity is clearly visible.

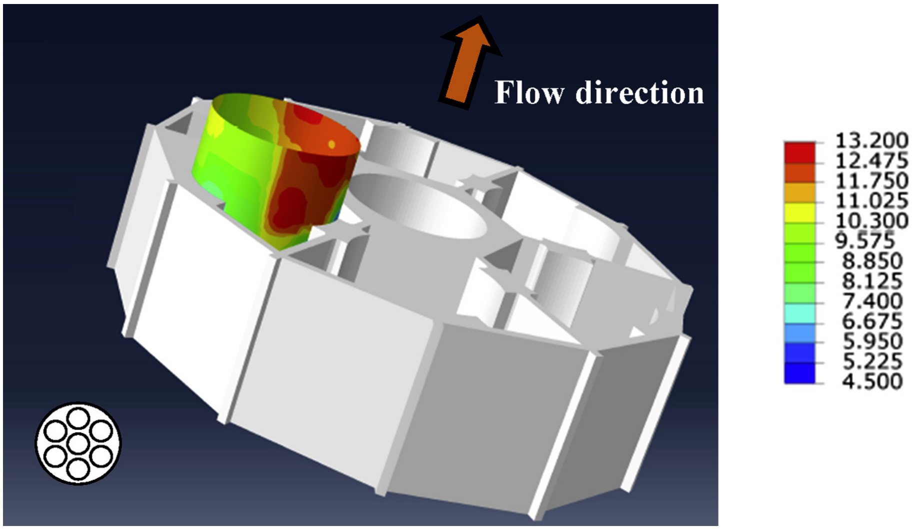


Fig. 11. By defining an integral quantity based on the FFT a measure of turbulence intensity can be derived.

1993);

$$Str^{-1} = \left(\frac{f_p D}{v^*}\right)^{-1} = 0.822\frac{S}{D} + 0.144 \tag{1}$$

where in f_p is the vortex passage frequency, D is the rod diameter, S the gap and v^* the friction velocity defined as $(\tau_w/\rho)^{-1/2}$ with τ_w being the wall shear stress. This work was developed keeping constant geometrical parameters and varying the coolant mass flow. Using Eq. (1) with the geometrical dimensions of the test section and for a flow rate of 2.7 kg/s, a frequency of 31.2 Hz is obtained. Important activity can be observed around this value, see Fig. 9. Despite the clear agreement, more studies need to be performed to confirm this finding since in the same frequency range some natural frequencies corresponding to mechanical vibration modes are found.

From Fig. 9 it can also be seen two peaks corresponding to frequencies around 110 Hz and 140 Hz. It is believed these frequencies are associated to vortex shedding generated by the geometrical change produced by the spacer grid. The difference in velocity between adjacent subchannels explains why the observed frequency is slightly different for different angular positions. Moreover, the spacer grid produces relatively low-scale vortices which have a major contribution to subchannel mixing downstream these elements (Mahmood, 2011).

In Fig. 10 the intensity and the associated frequency axial evolution of this type of structure is further investigated for different angular positions corresponding to an instrumented rod from the periphery. The selected angular positions plotted in the figure coincide with locations close to the sectors where the rod is supported by the spacer grid, where it was found the frequency activity was maximal. As can be noted, the intensity of the vortices rapidly decreases when moving downstream the spacer grid, which agrees with turbulence decaying theory. As a result, the presence of these geometry induced vortices is hardly detectable beyond 8 mm downstream the spacer grid.

Interestingly, the three-dimensional nature of these vortices is present in the fact there is a shift in the associated frequency at $\theta = 90^\circ$ when advancing downstream the spacer grid. In particular, for the actual set of measurements, the symmetry is somehow broken since the aforementioned shift is not observed at $\theta = 270^\circ$. This result supports the idea that any disturbance in the transversal direction may strongly affect the evolution of vortex shedding, which is closely related with the 3-dimensionality of the phenomena involved.

To give an idea of the turbulence intensity within a certain region of the measurement domain, the frequency activity associated to pressure fluctuations due to hydro-dynamical phenomena was integrated in the corresponding frequency window. In the case reported below, the FFT corresponding to a peripheral rod was integrated within 0 and 166 Hz. This quantity, Q defined in Eq. (2), is thus plotted in Fig. 9. As can be noted, the abrupt change in geometry induced by the supporting sectors from the spacer grid clearly enhances turbulence intensity (Fig. 11).

$$Q = \int_{0Hz}^{166Hz} g(f)df \tag{2}$$

5. Conclusions

In this work a novel technique for flow characterization in fuel assemblies is presented and their capabilities discussed. The main advantages which can be pointed out are:

- As a non-intrusive technique it can be applied with no assumptions regarding the measuring interference and therefore no corrections to the results are needed.
- A highly spatial and dynamical detailed results can be obtained by using affordable equipment and sensors.
- The measurement technique is robust regarding spatial misalignment and calibration of sensors.
- It can be used for complex geometries as those found in nuclear fuel rod elements.
- This technique is especially suitable for investigating three-dimensional phenomena such as the evolution of vortices in space.
- In addition, the measurement technique is also very suitable for characterizing correlation and interference of important phenomena affecting inter-subchannel cross-flow mixing. It needs to be emphasized the knowledge in this field is particularly scarce.
- This technique can provide important dynamical information useful for fuel bundles designers.
- The amount of spatial and dynamical information generated with this technique can be used as database for investigating the predicting capabilities of numerical codes and models.
- As drawbacks and limitations associated to this technique we can mention the following:
- The information collected is related to static pressure over the instrumented rods while most parameters used for flow characterization are based on the velocity field in the bulk of the flowing fluid.
- In order to exploit all the capabilities this technique can offer a dedicated automatized positioning system for the sliding pressure taps needs to be used.

The measurement technique developed in this work can help understanding flow mixing and spacer grids effect and could also provide a very complete experimental database with which numerical codes can be validated. Such a tool, with the aid of detailed CHF experiments, aids optimizing fuel bundle design enhancing the heat transfer and increase the critical heat flux, which would improve the fuel economy. As a concluding remark, we can mention this technique will not replace the existing ones but can successfully be used for generating complementary data and also is a valuable tool for elucidating the complex phenomena present in turbulent flow in nuclear fuel bundles.

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