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LDA measurements of coherent flow structures and cross-flow across the gap of a compound channel with two half-rods

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ABSTRACT

The enhancement of heat transfer from fuel rods to coolant of a Liquid Metal Fast Reactor (LMFR) decreases the fuel temperature and, thus, improves the safety margin of the reactor. One of the mechanisms that increases heat transfer consists of large coherent structures that can occur across the gap between adjacent rods. This work investigates the flow between two curved surfaces, representing the gap between two adjacent fuel rods. The aim is to investigate the presence of the aforementioned structures and to provide, as partners in the EU SESAME project, an experimental benchmark for numerical validation to reproduce the thermal hydraulics of Gen-IV LMFRs. The work investigates also the applicability of Fluorinated Ethylene Propylene (FEP) as Refractive Index Matching (RIM) material for optical measurements.

The experiments are conducted on two half-rods of 15 mm diameter opposing each other inside a Perspex box with Laser Doppler Anemometry (LDA). Different channel Reynolds numbers between Re = 600 and Re = 30,000 are considered for each P/D (pitch-to-diameter ratio).

For high Re, the stream wise velocity root mean square v_{rms} between the two half rods is higher near the walls, similar to common channel flow. As Re decreases, however, an additional central peak in v_{rms} appears at the gap centre, away from the walls. The peak becomes clearer at lower P/D ratios and it also occurs at higher flow rates. Periodical behaviour of the span wise velocity across the gap is revealed by the frequency spectrum and the frequency varies with P/D and decreases with Re. The study of the stream wise velocity component reveals that the structures become longer with decreasing Re. As Re increases, these structures are carried along the flow closer to the gap centre, whereas at low flow rates they are spread over a wider region. This becomes even clearer with smaller gaps.

1. Introduction

The rod bundle geometry characterises the core of LMFBR, PWR, BWR or CANDU reactors, as well as the steam generators employed in the nuclear industry. In the presence of an axial flow of a coolant, this geometry leads to velocity differences between the low-speed region of the gap between two rods and the high-speed region of the main sub-channels. The shear between these two regions can cause streaks of vortices carried by the stream. Generally those vortices (or structures) develop on either sides of the gap between two rods, forming the so-called *gap vortex streets* (Tavoularis, 2011). The vortices forming these *streets* are stable along the flow, contrary to free mixing layer conditions where they decay in time. Hence the adjective *coherent*. The formation mechanism of the gap vortex streets is analogous to the Kelvin-Helmholtz instability between two parallel layers of fluid with distinct velocities (Meyer, 2010). The stream-wise velocity profile must have an inflection point for these structures to occur, as stated in the Rayleigh's instability criterion (Rayleigh, 1879).

Moreover, a transversal flow of coherent structures across the gap between two rods can also occur. In a nuclear reactor cross-flow is important as it enhances the heat exchange between the nuclear fuel and the coolant. As a result, the fuel temperature decreases improving the safety performance of the reactor.

Much research has been done in studying periodic coherent structures and gap instability phenomena in rod bundles resembling the core of LMFBRs, PWRs, BWRs and CANDUs. Rowe et al. (1974) measured coherent flow structures moving across a gap characterised by a P/D of 1.125 and 1.25. A static pressure instability mechanism was proposed by Rehme to explain the formation of coherent structures (Rehme, 1987). Möller measured the air flow in a rectangular channel with 4 rods (Möller, 1991). The rate at which the flow structures were passing increased with the gap size. The instantaneous differencies in velocity and vorticity near the gap, responsible of the cross-flow, were associated with a state of *metastable equilibrium*. Recently, Choueiri gave an analogous explanation for the onset of the gap vortex streets (Choueiri

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Nomenclature

Latin symbol

A	Flow area, mm^2
$D_{H,GAP}$	Gap hydraulic diameter, m
d_0	Laser beam diameter, mm
f	Flow structure frequency, Hz
H, L	Test section side dimensions, mm
$\mathscr{L}$	Flow structure length, m
l	LDA probe length, mm
N_s	Number of collected samples, –
P/D	Pitch-to-diameter ratio, –
R_i	Inner half-rod diameter, mm
R_{rod}	Half-rod diameter, mm
S	Frequency spectrum, s
t	thickness, mm
$\overline{U}$,U_{rms}	Mean and rms generic velocity, m/s
u^*	friction velocity, m/s
$\dot{V}$	Flow rate, l/s
v	Stream-wise velocity component, m/s
W	Rod-to-rod distance, mm
X, Z	Span-wise and normal-to-the-gap coordinates, mm
z^+	Non dimensional wall distance, –

Non dimensional number

Re	Reynolds
Str	Strouhal

Greek symbol

α	Laser half beam angle in air, °
β	Laser half beam angle through Perspex, °
γ	Laser half beam angle in water, °
η	Refractive index, –
λ	Laser wavelength, nm
μ	Dynamic viscosity, Pa·s
ρ	Density, kg/m^3
σ	Standard deviation around the mean frequency, Hz
ε_m,ε_{rms}	95% conf. interval for mean and rms values, –
ξ,ε,ω,δ	Angles pertaining to light refraction through FEP, °

Abbreviation

BWR	Boiling Water Reactor
CANDU	Canada Deuterium Uranium
CAMEL	Crossflow Adapted Measurements and Experiments with LDA
CFD	Computational Fluid Dynamics
FEP	Fluorinated Ethylene Propylene
PMMA	Polymethyl Methacrylate
LDA	Laser Doppler Anemometry
LMFR	Liquid Metal Fast Reactor
LES	Large Eddy Simulation
PWR	Pressurized Water Reactor
RIM	Refractive Index Matching
URANS	Unsteady Reynolds-Averaged Navier-Stokes

Subscript

w	Pertaining to water
BULK	Bulk flow region
GAP	Gap flow region
rms	Root mean square
a	Pertaining to air
p	Pertaining to the LDA probe
sp	Pertaining to span-wise component
st	Pertaining to stream-wise component
infl	Stream-wise velocity profile inflection point
min	Lower limit of flow structure lengths
Max	Upper limit of flow structure lengths

and Tavoularis, 2014). Baratto investigated the air flow inside a 5-rod model of a CANDU fuel bundle (Baratto et al., 2006). The frequency of passage of the coherent structures was found to decrease with the gap size, along the circumferential direction. Gosset and Tavoularis (2006), and Piot and Tavoularis (2011) investigated at a fundamental level the lateral mass transfer inside a narrow eccentric annular gap by means of flow visualization techniques. The instability mechanism responsible for cross-flow was found to be dependent on a critical Reynolds number, strongly affected by the geometry of the gap. Parallel numerical efforts have been made by Chang and Tavoularis with URANS (Chang and Tavoularis, 2005) and by Merzari and Ninokata with LES (Merzari and Ninokata, 2011) to reproduce the complex flow inside such a geometry. However, the effects that the gap geometry has on cross-flow, and in particular the P/D ratio, has been debated long since and yet, a generally accepted conclusion is still seeked. Moreover detecting lateral flow pulsations is yet an hard task (Xiong et al., 2014).

This work aims to measure cross-flow as well as the effects that Reynolds and P/D have on the size of the structures. Near-wall measurements in water are performed with the non-intrusive LDA measurement system inside small gaps and in the presence of FEP.

2. Experimental setup

The experimental apparatus is composed by the test setup, CAMEL, and by the Laser Doppler Anemometry system. The water enters the facility from two inlets at the bottom and flows inside the lateral subchannels and through the gap in between. The outlets are located at the top and the water is collected in an upper vessel. The flow rate is manually adjusted by two valves at the inlet lines and monitored by two pairs of magnetic flow-meters (for inlet and outlet lines). At the measurement section, one of the two half-rods is made of FEP (Fig. 1). A scheme of the loop is pictured in Fig. 2 FEP is a Refractive Index Matching material since it has the same refractive index of water at 20 °C (η_{FEP} = 1.338 (Mahmood et al., 2011); η_w = 1.333 (Tilton and Taylor, 1938) with 532 nm wavelength); it can be employed to minimise the refraction of the laser light. To reduce the distortion of light even more, the FEP half-rod is filled with water. The spacing between the rods can

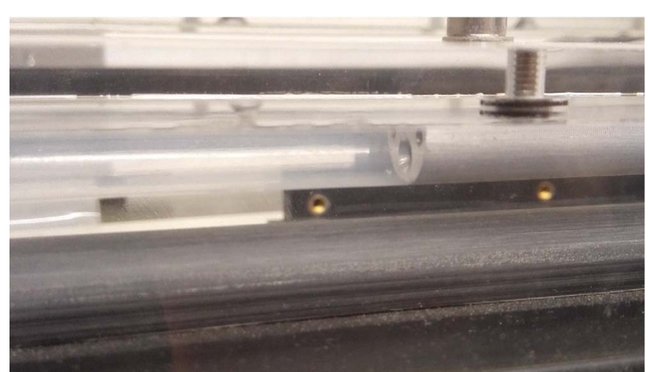

Fig. 1. Hollow half-rod of FEP seen from the outside of the transparent test section: of the two half-rods the top grey one is the rod hosting the FEP section.