The KNOO Project
At
The University of Manchester

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What is KNOO?

KNOO is a four-year initiative set-up to maintain and develop know-how relevant to nuclear power generation. The project consists in a close collaboration between several universities in UK and key industrial and governmental stakeholders. KNOO is founded through the “Towards a Sustainable Energy Economy Program” of Research Councils UK.
KNOO in numbers

- Collaboration between seven universities among all UK
- Budget of £6.1 million (€7.5 million): KNOO is the single largest commitment to fission reactor research in UK in the last thirty years.
- More than 50 investigators involved
- More than 70 PhD projects financed
- Structured in four different Works Package covering all the aspects of nuclear engineering.
KNOO is divided into four Work Packages:

- **WP1**: Fuel Thermal-hydraulics and reactor Systems;
- **WP2**: Materials performances and Monitoring Reactors Conditions;
- **WP3**: An integrate approach to waste immobilization and management;
- **WP4**: Safety and performances for a new generation of Reactor Design.

http://www.knoo.org/
Activities of the MACE CFD Group in KNOO can be divided into:

1. Creation of databases (Refined LES) for RANS validation
   - KNOO Test cases (Heat Transfer)
     http://cfd.mace.manchester.ac.uk/Main/KnooTestCases

2. Best Practise Guidelines (BPG) for CFD in nuclear applications.
   - http://cfd.mace.manchester.ac.uk/Main/KnooWorkshop

3. Generation IV design.

4. Performance improvements of actual reactor configurations

5. TWiki portal of the Project:
   - http://cfd.mace.manchester.ac.uk/Main/KnooProject
Refined LES of Natural Convection and induced re-laminarized flow.

- Heated vertical pipe flow
- Buoyancy opposed wall jet
- Cohaxial heated cylinder
- Tilted cavity
Advanced Gas Reactors (AGRs) (A. Keshmiri)

**General:**
- Working fluid: CO₂
- Re=1e+6 ; based on $D_h$
- Flow direction: Upward

**Mass flow rates:**
- Fuel channels: 3910 kg/s
- Net circular flow: 4270 kg/s
- Peak channel flow: 14.1 kg/s

**Working bulk temperatures:**
- Channel inlet: 334°C
- Channel outlet: 635°C
- Peak Temp: 661°C

**Working pressures inside pressure vessel:**
- Bottom slab: 45.2 bar
- Top slab and walls: 42.5 bar

*"The Safety of the AGR by J M Bowerman (1982)"*:
AGR fuel assembly configurations (A. Keshmiri)

Three different types of configurations for fuel pins:

1) “Parallel”

2) “Transverse”

3) “Multi-start” : 12 different helixes with different starting points
Preliminary Results “Transverse Configuration”
(A. Keshmiri)

2D Approach with a Low-Reynolds k-ε model
Rod Bundle arranged in a triangular array

• Experimental work:


• CFD work (URANS):


From II

\[ \text{St} = \frac{fD}{U_{B,\text{gap}}} = 0.93 \quad \text{for} \quad \frac{P}{D} = 1.06 \]
Rod Bundle: Cases definition

Two different geometrical configuration

1. \( P/D = 1.06 \)
   - I. **LES @ Re = 6000** Mesh size ~ 2 Millions cells with Heat transfer.
     - \( 0.75 < \Delta r + < 1.06 \)
     - \( 6 < r \Delta \theta + < 10 \)
     - \( 16 < \Delta x + < 22.5 \)
   - II. **Hybrid @ Re = 6000** Mesh size ~ 0.35 Million cells with Heat transfer
     - \( 0.8 < \Delta r + < 1.3 \)
     - \( 15 < r \Delta \theta + < 20 \)
     - \( 40 < \Delta x + < 60 \)
   - III. **Hybrid @ Re = 39000** Mesh size ~ 0.9 Million cells no Heat transfer
     - \( 0.8 < \Delta r + < 1.2 \)
     - \( 20 < r \Delta \theta + < 25 \)
     - \( 50 < \Delta x + < 70 \)

2. \( P/D = 1.15 \)
   - I. **LES @ Re = 6000** Mesh size ~ 1.4 Million cells no Heat transfer
     - \( 0.8 < \Delta r + < 1.1 \)
     - \( 6.5 < r \Delta \theta + < 10 \)
     - \( 16 < \Delta x + < 22.5 \)

All the domains have a stream-wise length equal to 12 times the hydraulic diameter
The Hybrid RANS-LES method is following a usual LES decomposition in large scale and sub-grid part:

\[ u_j = \overline{u_j} + u'_j \]

The anisotropic part of the residual stress tensor and residual heat flux can be decomposed following a Schumann decomposition:

\[
\begin{align*}
\tau_{ij}^r &= -2\nu_r F_b \left( S_{ij} - \langle S_{ij} \rangle \right) - 2\nu_a (1 - F_b) \langle S_{ij} \rangle \\
\sigma_j &= -F_b \kappa_r \frac{\partial}{\partial x_j} \left( \overline{T} - \langle T \rangle \right) - (1 - F_b) \kappa_a \frac{\partial \langle T \rangle}{\partial x_j}
\end{align*}
\]

\[ \nu_r = (C_s \Delta)^2 \sqrt{2s'_{ij} s'_{ij}} \]

Sub-grid viscosity

\[ \nu_a = C_\mu \varphi kT \]

RANS viscosity computed from the mean velocity field \((\varphi = \overline{v^2} / k)\)

For the eddy conductivity a simply turbulent Prandtl number analogy is used:

\[
\begin{align*}
\kappa_r &= \frac{\nu_r}{Pr_t} \\
\kappa_a &= \frac{\nu_a}{Pr_t}
\end{align*}
\]
The merging between the two velocity fields is done through a blending function to obtain a smooth transition:

\[ F_b = \tanh \left( C_l \frac{L_t}{\Delta} \right)^n \]

Turbulent RANS length scale computed with a relaxation model based on \( \frac{v^2 - f}{\varepsilon} \):

\[ L_t = \varphi k_i^{3/2} / \varepsilon \]

Filter width:

\[ \Delta = 2V_0 l^{1/3} \]

Empirical constants computed in order to match the stress profile for channel flow @ \( Re = 395 \):

\[ C_l = 1.5, \quad n = 1 \]

Hybrid results with mesh Size ~ 0.1 mil cell

Under-resolved standard LES

Relevant data points:
- DNS
- M0 LES
- M1 LES
- M2 LES

Graphs showing flow profiles at different Reynolds numbers.
Results: Flow Pulsation in the mid-plane

LES @ Re = 6000

P/D=1.06
(Cross velocity)

Hybrid @ Re = 6000

(Cross velocity)
Power spectra azimuthal velocity

<table>
<thead>
<tr>
<th></th>
<th>LES6K</th>
<th>LESWPD</th>
<th>HYB6K</th>
<th>HYB39K</th>
<th>EXP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{St} = \frac{fD}{U_{B,\text{gap}}}$</td>
<td>0.98-1.96</td>
<td>/</td>
<td>0.91-1.85</td>
<td>0.92-1.94</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Length scales
Results: Average Field (LES P/D = 1.06 Re = 6000)

\[ \frac{\langle U \rangle}{U_b} \]

\[ \frac{T_{w,m} - T}{(T_{w,m} - T_b)} \]

\[ \langle u\theta \rangle \]

\[ \langle \theta \theta \rangle \]

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</tr>
</thead>
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<tr>
<td>( \tau_w/0.5\rho U_B^2 )</td>
<td>0.0086</td>
<td>0.0025</td>
<td>0.0106</td>
<td>0.0104</td>
<td>0.0057</td>
</tr>
<tr>
<td>( U_{B,\text{gap}} / U_B )</td>
<td>0.75</td>
<td>0.89</td>
<td>0.77</td>
<td>0.83</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Results: Reynolds Stress LES P/D=1.06

\[
\begin{align*}
\langle uu \rangle \\
\langle uv \rangle \\
\langle vv \rangle \\
\langle uw \rangle \\
\langle vw \rangle \\
\langle ww \rangle
\end{align*}
\]
SFR assembly (with C. Penniguel)

Proposal of EdF for the GEN IV reactors

Same geometry presented before with the addition of a wire wrapped around the fuel pin.
Conclusions.

**LES**
- Flow Fluctuations detected,
- Presence of a second dominant frequency has to be verified with bigger domain.

**Hybrid**
- Flow pulsations detected and dominant frequency in according with LES
- Improvement of the blending function for RANS/LES coupling using an elliptic blending (following the work of F. Billard on the $\alpha$ parameter)

**KNOO – Heat transfer test cases: expansion of the TWiki portal.**

**Evaluating possible advantage/disadvantages of polyhedral cells**

**AGRs: complete 3D study to evaluate possible improvements of the geometrical configuration.** (A. Keshmiri)
Reynolds Stress Hybrid P/D=1.06 Re=39000

\[ \langle uu \rangle \]

\[ \langle uv \rangle \]

\[ \langle vw \rangle \]

\[ \langle vv \rangle \]

\[ \langle uw \rangle \]

\[ \langle ww \rangle \]