Use of EPICS and python technology for development of a computational toolkit for high heat flux testing of plasma facing components

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Outline of the talk

• Introduction
  – Requirements of high heat flux testing of PFC
  – Critical heat flux phenomena
  – Context for Parametric optimization

• Computational toolkit description
  – Design
  – Implementation: EPICS, Python and pyepics

• Results

• Future scope of work and conclusion
Computational Simulations and virtual Experimentation

• Computer simulation facilitate testing of all the feasible test cases. It is a useful aid for the predicting experiments where operational cost is very high.

• Provides flexibility of parameters variation and understanding of phenomena and operational regimes

• Open source technologies are matured and provides rich programming APIs
Divertors in a tokamak

- Divertors are important plasma facing components.
- Used to exhaust He ash and heat flux and control of impurities and fuel density.
- Absorb high heat load to improve performance of tokamak

Figure 1: Main components of a ITER tungsten divertor cassette [1]
Complexities in Divertor design

- Subject to high heat load of 5-20 MW/m²
- Design challenges:
  - Requires materials to withstand intense heat load
  - **Cooling system to protect system from burnout and environment issues**
- Operational stability under:
  - Static load conditions of plasma
  - Transient load conditions (in case of instability)

Tungsten Macro brush

Tungsten Monoblock
Critical Heat Flux (CHF) phenomena

- Describes loss of liquid layer or phase change at the wall which can lead to decrease the efficiency of heat transfer thus burn out.

- Accurate prediction of CHF is must for a safe design.
Thermal hydraulic correlations

- Convection heat transfer coefficient is given by

$$h = \frac{Nu \cdot k}{d} \quad Q = m' \cdot Cp \cdot \Delta T$$

Where,

$Nu$ - Nusselt number
$k$ - Conductivity of coolant (W/mK)
$d$ - Inside diameter of the tube (m);

$Q = \text{Rate of heat energy removed (J/s)}$
$m'$ = mass flow rate (Kg/s)
$Cp = \text{Specific Heat Capacity (J/Kg.K)}$
$\Delta T = \text{coolerant temperature rise}$

- The Reynolds number ($Re$), Prandtl number ($Pr$) and the Nusselt Number ($Nu$) are given by the relations

$$Re = \frac{\rho \cdot V \cdot d}{\mu} \quad Pr = \frac{\mu \cdot Cp}{k} \quad Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$$

Where,

$\rho$ – Density of the fluid
$\mu$ – Dynamic viscosity (Kg/m.s)
$V$ – Velocity of the fluid (m/s)
$d$ – Inside diameter of the tube (m)
k – Conductivity of coolant (W/mK)
Tong-75 CHF correlation [3]

CHF model for one sided heating condition of fusion devices are modeled by many relations. Tong-75 correlation has shown good agreement with experiments. It is a semi empirical model and also used for thermo-hydraulic analysis of ITER divertors.

\[
CHF_w = 0.23 f G H_f g \left( 1 + 0.00216 \left( \frac{P}{P_c} \right) \right)^{1.8} \text{Re}^{0.5} J a 
\]

\[
f = 8 \text{Re}^{-0.06} \left( \frac{d_h}{d_o} \right)^{0.32}
\]

\[
J a = \frac{\rho_f C_p (T_{\text{Sat}} - T)}{\rho_g H_{fg}}
\]

\[
\text{Re} = \frac{GD}{\mu_f}
\]

Where \( CHF_w \) is the critical heat flux at the tube wall, \( G \) is the coolant mass velocity, \( T \) is the local coolant temperature, \( P \) is the local coolant pressure, \( T_{\text{sat}} \) is the saturation temperature corresponding to \( P \), \( H_{fg} \) is the latent heat of vaporization of water at \( T_{\text{sat}} \), \( P_c \) is the critical pressure, \( \text{Re} \) is the Reynold number, \( d_h \) is the hydraulic diameter, \( \mu_f \) is the water viscosity at \( T \), \( J a \) is the Jakob number, \( \rho_f \) is the water density at \( T \), \( \rho_g \) is the vapour density at \( T_{\text{sat}} \), \( C_p \) is water specific heat, \( d_o \) is reference diameter.
Computational complexity and parametric Optimization

- **Computational complexity:**
  - Non-linear inter parameter dependency and curve fitting required for the CHF computation.
  - Thermo physical properties for water are taken from NIST database.

- **Parametric Optimization:**
  - Find best local cooling condition viz. Pressure, flow and temperature for maximum heat transfer using parametric optimization of CHF relation such that steady state wall heat flux is maintained.
  - Constraint Optimization by linear approximation (COBYA) technique is used for optimization for the parametric optimization.

Figure 3: Schematic illustrating the peaking of heat flux to the coolant for a given incident heat flux.
High Heat flux Test facility (HHFTF) at IPR

- High heat flux facilities is commissioned to test the thermal performance of divertor mock up and cooling system under intense heat exposure.

- It will use electron gun (200KW) as source and high pressure and temperature water cooling system (under procurment).

Need to design an integrated toolkit enriched with computational routines and an experimental framework for simulation and interface to the sensors and transducers.

Figure 4: Vacuum System of HHFTF

Figure 5: 200 kW Electron Gun
Software development targets

• Develop computation code to predict the optimum cooling system parameters of pressure, temperature and flow.

• Graphical user interface

• I&C hardware integration and simulation flexibility.

• Provide a virtual simulation of the system operation using optimized parameters.

• Development using open source softwares and relevant to fusion technology road map
Design Description

Activity Diagram

1. Analyze
2. Read operational schedule consisting of test mockup, heat source, and cooling system specifications
3. Perform the calculation of incident heat flux and critical heat flux
4. Obtain the cooling system parameters by optimizing the CHF model
5. Simulate the operation of the experiments
6. [true] Run actual experiment

Architectural Diagram

1. Computational Processing Module
2. Control System Module
3. User Interface
4. Data Base Module
5. Virtual or actual I/O Hardware
Implementation (1/3)

EPICS

(Experimental Physics and Industrial Control System)

• A rich control system development framework for I&C integration, Open source, Used at around ~350 labs world wide (including ITER)

• Rich tools for data display, archivals and alarms are available.

• Support a good user interface toolkit like control system studio, which is based on eclipse and has python interface.

• I/O simulation support
Implementation (2/3)

• **Python:**
  - Used for computational processing module development
  - Support object oriented and modular programming
  - Scripting language, clear indentation, popular and open source
  - Rich computational libraries: Numpy, Scipy Matplotlib
  - Support test framework e.g. NOSE

• **Postgress Database:**

• Used to hold NIST database.
Implementation (3/3)

- **pyepics:**
  - This library is used to provide the interface between EPICS and python.
  - Used at university of chicago
  - Offers object oriented and functional form of interface.
  - And process variable processing capabilities.
  - Well documented and can be used where extensive simulation is required.
Results: Curve fitting
Results: Heat flux calculations

\[ \text{CHF}_{w} = 0.23/GH_{fs} \left( 1 + 0.00216 \left( \frac{P}{P_c} \right)^{1.8} Re^{0.5}Ja \right) C_f \]

Total Heat Flux: 26.75 MW/m²
Results: CHF vs Pressure and optimization

Figure: CHF Optimization and Pattern Visualization
Results: Parametric Optimization

Figure: Parametric Optimization
Results: Heat transfer simulation on optimised set points
Validation

• NOSE frame work of python is used for automated testing of simulated test cases and heat transfer coorelations.

• Published data of international 2006 CHF database table is used as a referance for validation.

• Results of optimization are validated using graph plotting.
Conclusion and Future directions

- A integrated tool kit having experimental and computational features is presented. Useful for the high heat flux test experiments of similar nature.
- The parametric optimization offers the required parameters for the operation.
- The toolkit can be extended for
  - Advanced cooling tube geometries
  - Simulation capabilities
  - Multi-objective optimization features.
References


Thanking you