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 understading of phenomena and operational regimes
- Open source technologies are matured and provides rich programming APIs

Divertors in a tokamak

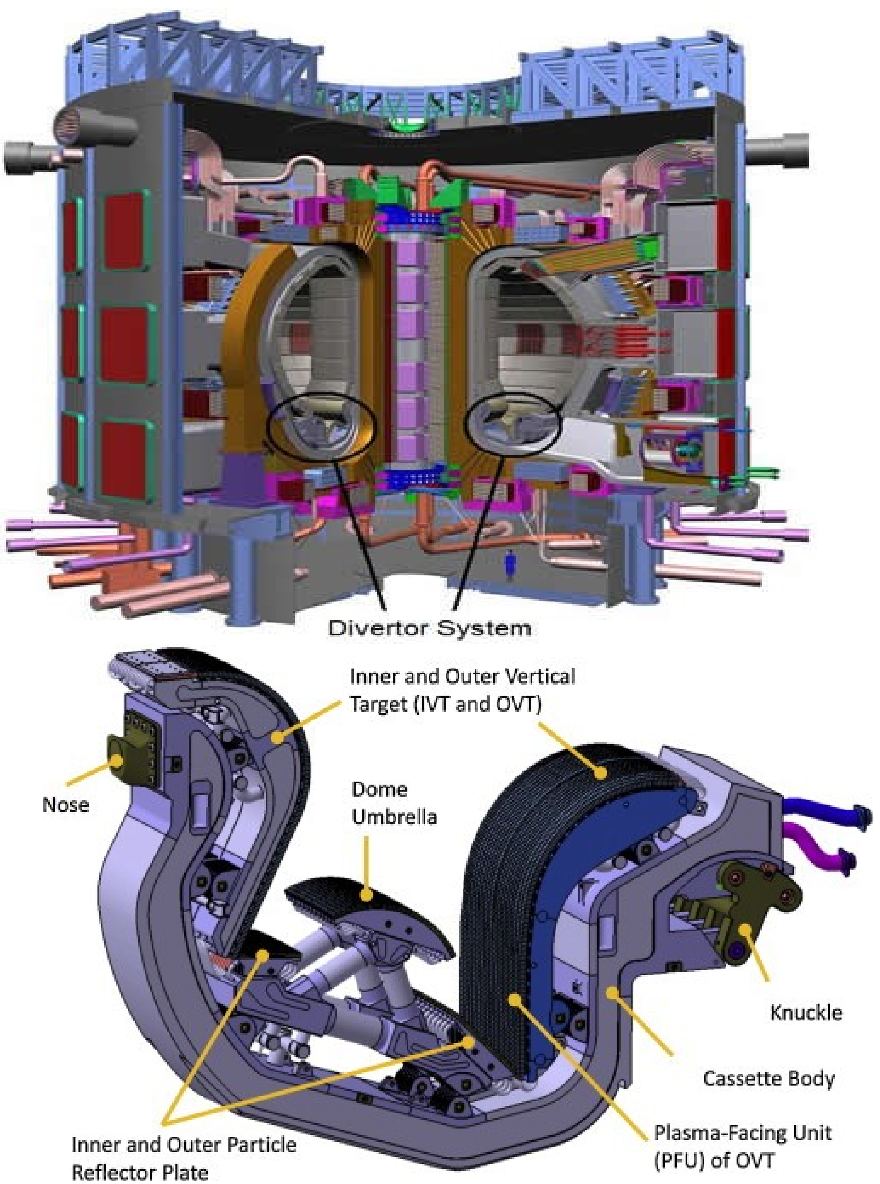


Figure 1: Main components of a ITER tungsten divertor casesette [1]

- 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

Complexities in Divertor design

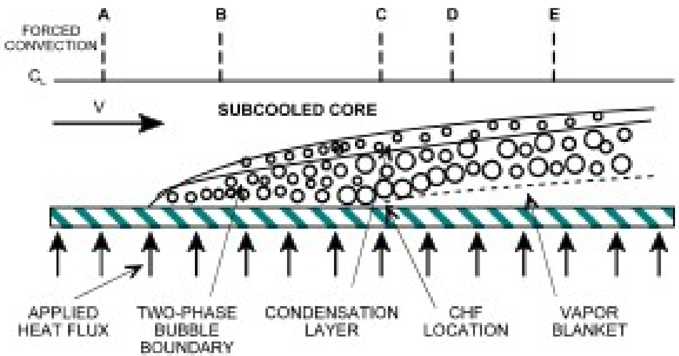
- Subject to high heat load of 5-20 MW/m^2
- Design challanges:
  - Requires materials to withstand intense heat load
  - **Cooling system to protect system from burnout and environment issues**
- Operational stability under:
  - Static load conditions of plasma
  - Transient load conditions

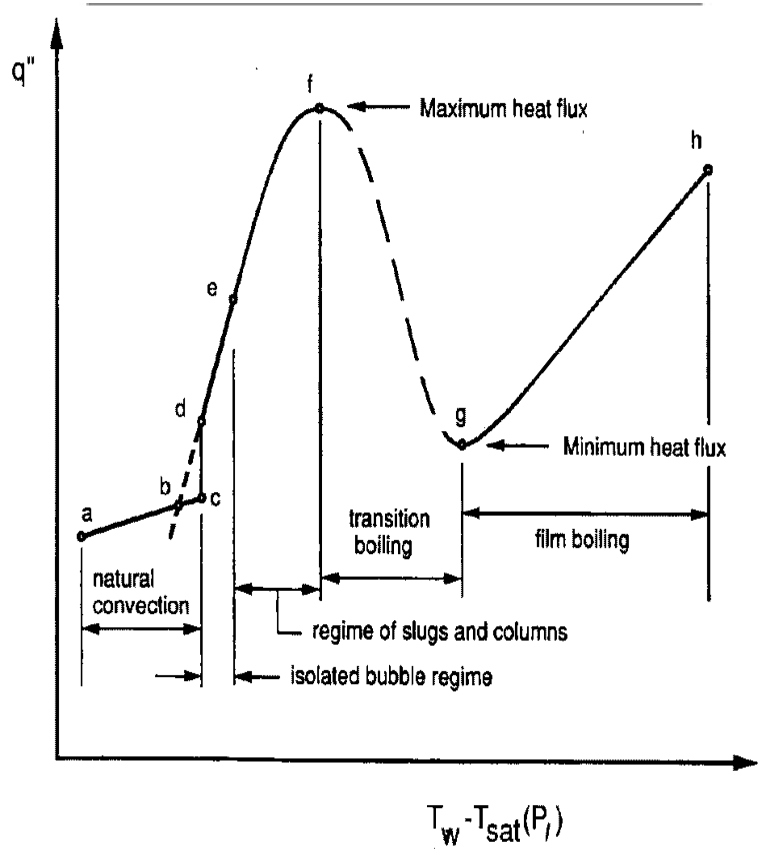
  (in case of instability)

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 head transfer thus burn out.

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

Thermal hydraulic correlations

- Convection heat transfer coefficient is given by

$h = Nu.k / d$ **$Q = m'Cp.\Delta T$**

Where,

Nu - Nusselt number

k - Conductivity of coolant (W/mK)

d - Inside diameter of the tube (m);

Q = Rate of heat energy removed (J/s)
m' = mass flow rate (Kg/s)
Cp = Specific Heat Capacity (J/Kg.K)
ΔT = coolant temperature rise

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

$Re = \rho Vd/\mu$ **$Pr = \mu Cp/k$** **$Nu = 0.023 * Re^{0.8} * Pr^{0.4}$**

Where,

ρ – Density of the fluid

μ – 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.

$$CHF_w = 0.23\, f G H_{fg} \left(1 + 0.00216 \left(\frac{P}{P_C}\right)^{1.8} \mathrm{Re}^{0.5} Ja\right)$$

$$f = 8\mathrm{Re}^{-0.06} \left(\frac{d_h}{d_o}\right)^{0.32}$$

$$Ja = \frac{\rho_f}{\rho_g} \frac{C_p \left(T_{Sat} - T\right)}{H_{fg}}$$

$$\mathrm{Re} = \frac{GD}{\mu_f}$$

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_{sat} is the saturation temperature corresponding to P, H_{fg} is the latent heat of vaporization of water at T_{sat}, Pc is the critical pressure, Re is the Reynold number, d_h is the hydraulic diameter, μ_f is the water viscosity at T, Ja is the Jakob number, ρ_f is the water density at T, ρ_g is the vapour density at T_{sat}, C_p is water specific heat, do 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

$$\{T, C_p\}, \{T, \rho\}, \{T_{sat}, \mu_f\}, \{P, T_{sat}\}, \{P, H_{fg}\}, \{\rho, T_{sat}\}$$

- **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.

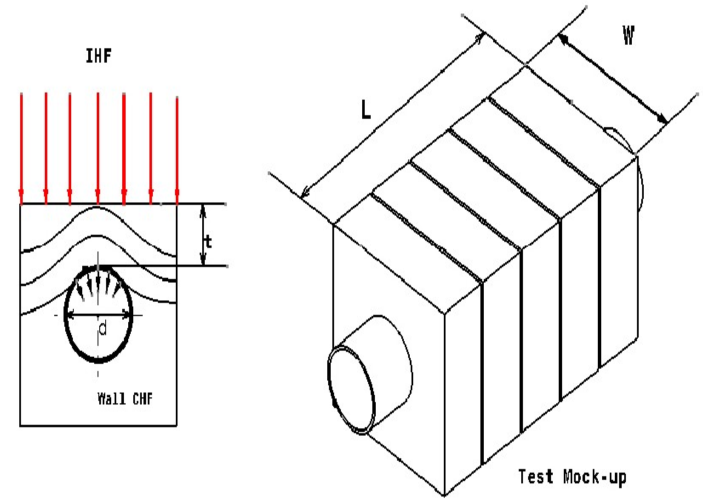


Figure 3: Schematic illustrating the peaking of heat flux to the coolant for a given incident heat flux

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 intence 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

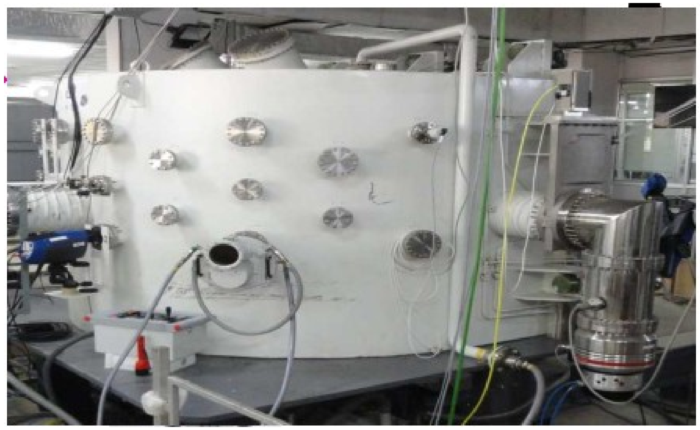


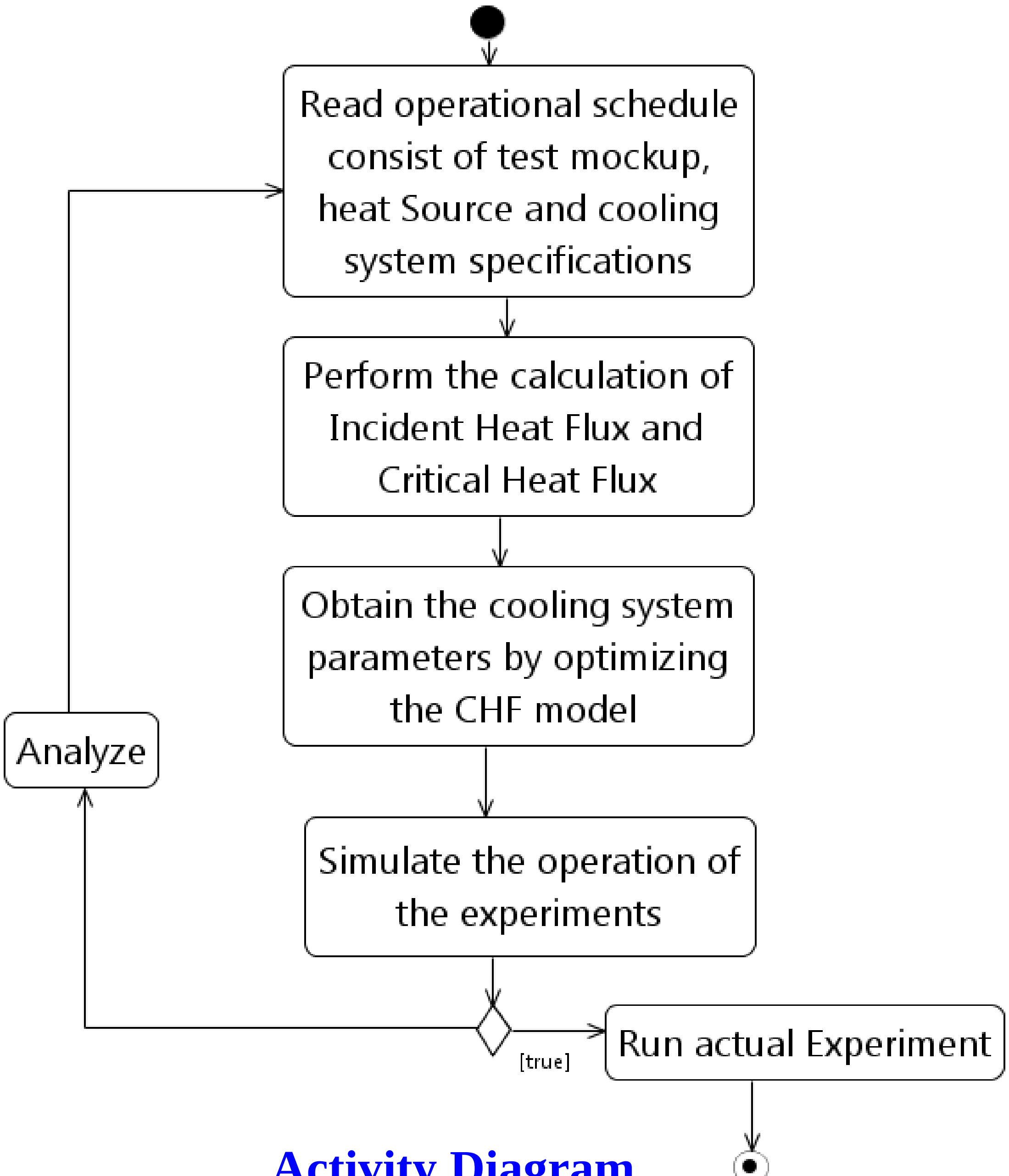
Figure 4: Vacuum System of HHFTF

Figure 5: 200 kW Electron Gun

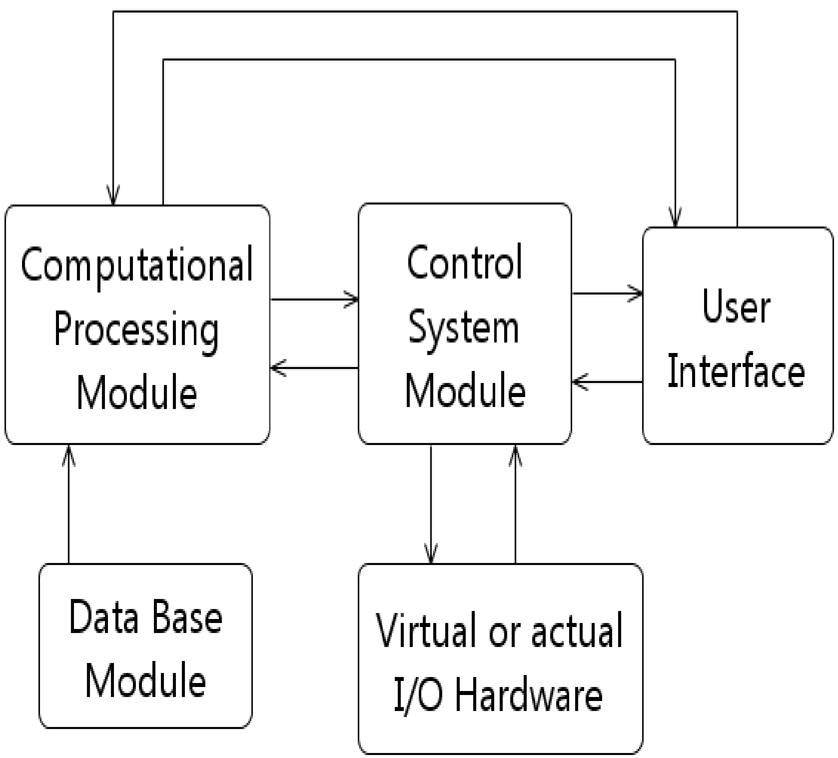
Software development targets

- 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

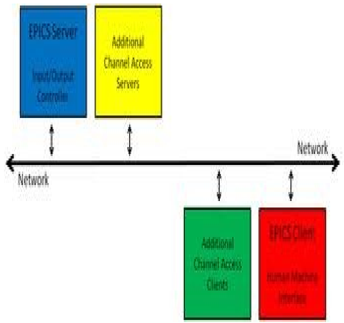
Design Description



Activity Diagram



Architectural Diagram



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

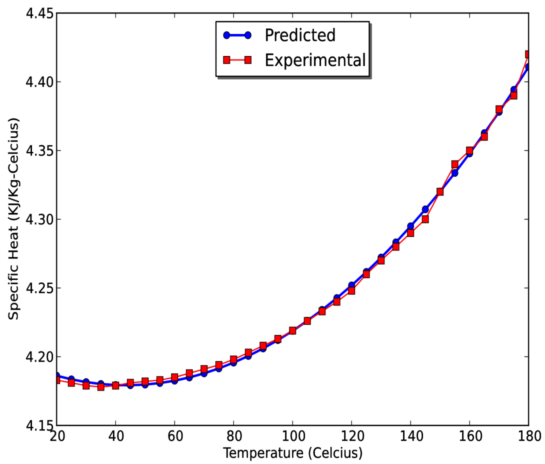
Implementation (2/3)

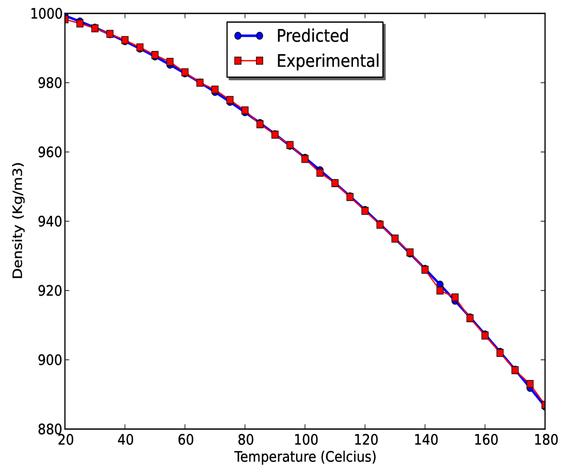
- **Python:**
  - Used for computational processing module development
  - Support object oriented and modular programming
  - Scripting language, clear indentation, popular and open source
  - Rich computional libraries: Numpy , Scipy Matplotlib
  - Support test framework e.g. NOSE
- **Postgress Database:**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

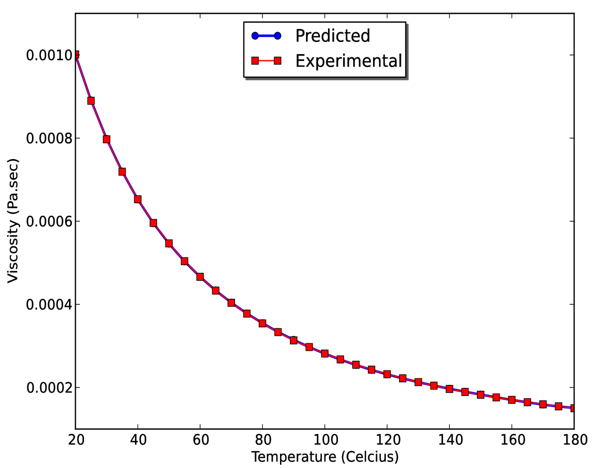
Implementation (3/3)

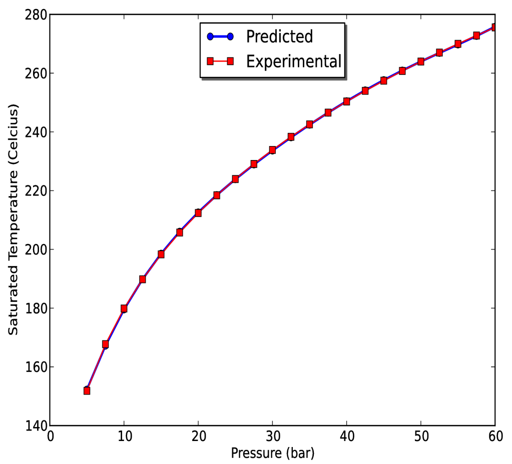
- **pyepics:**
  - This library is used to provide the interface between EPICS and python .
  - Used at university of chicago
  - offers object oriented and functional form of interface.
  - And process variable processing capabilities.
  - Well documented and can be used where extensive simulation is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

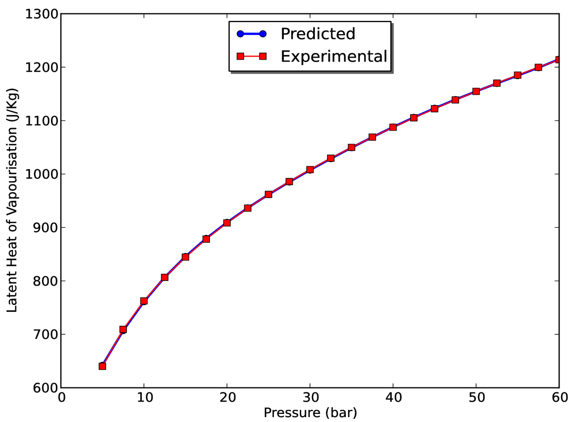
Results : Curve fitting

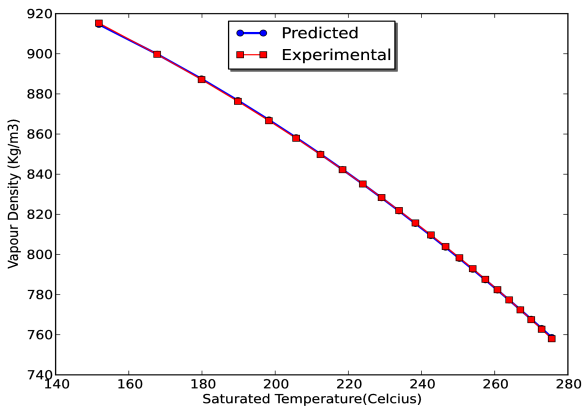




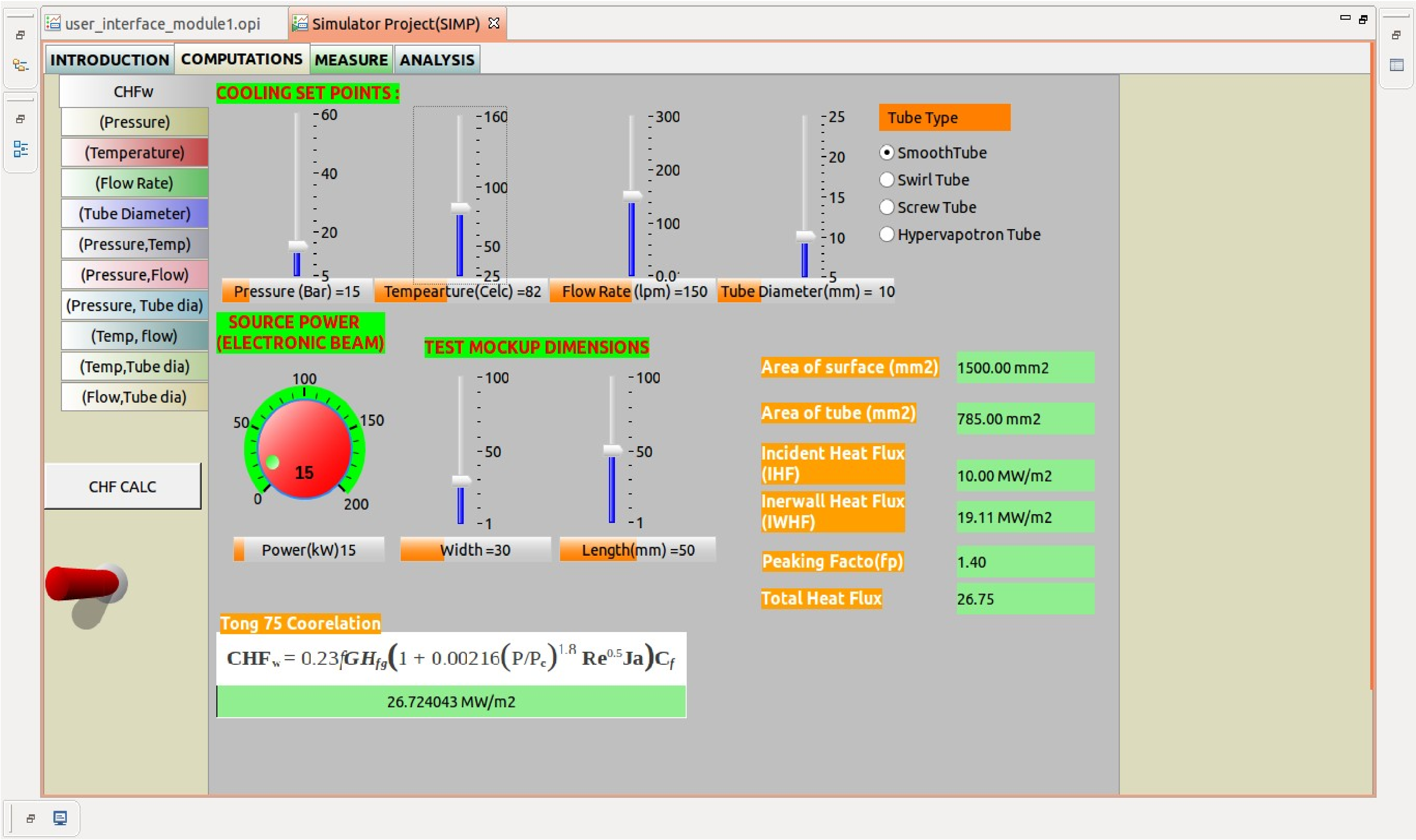








Results : Heat flux calculations



Results: CHF vs Pressure and optimization

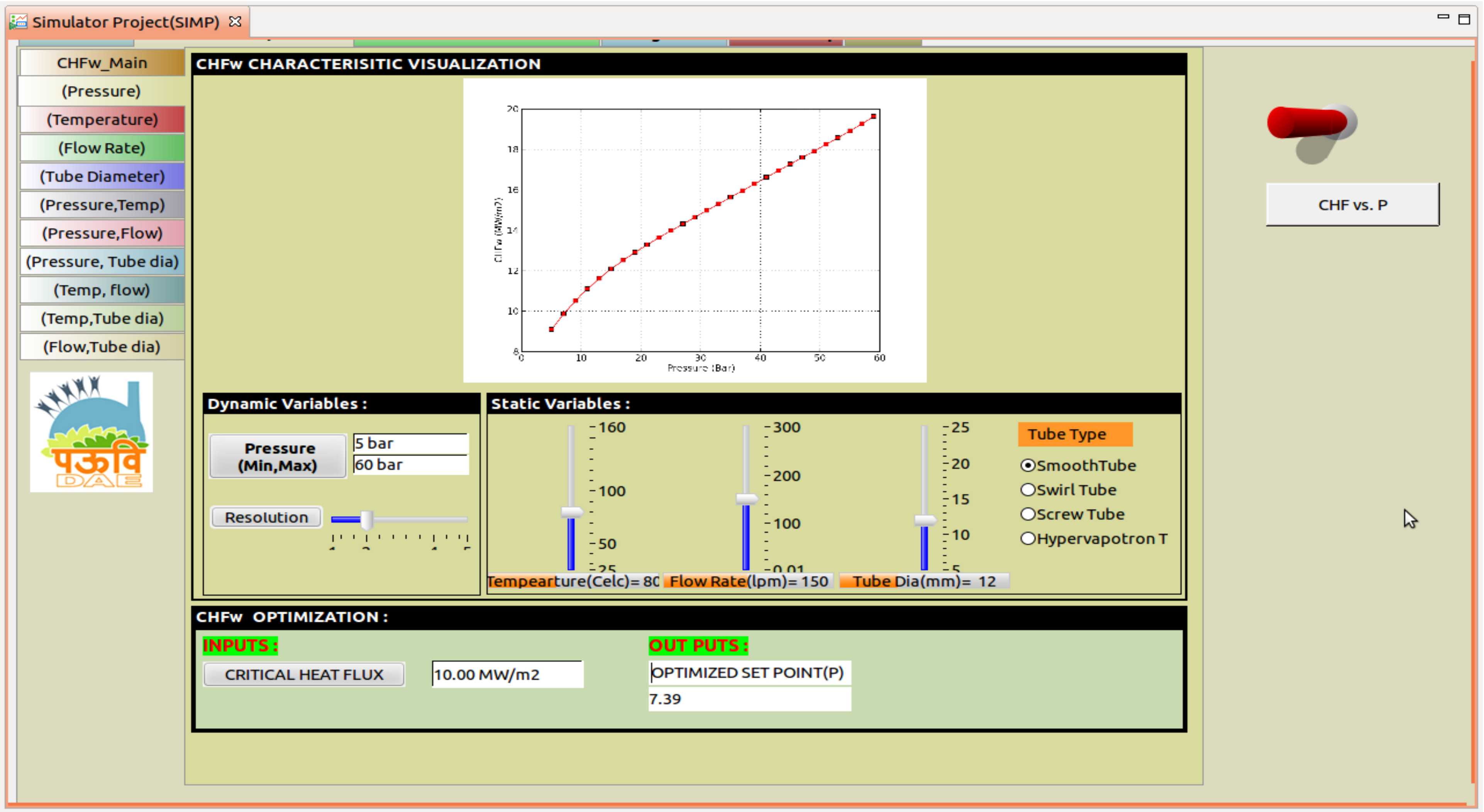
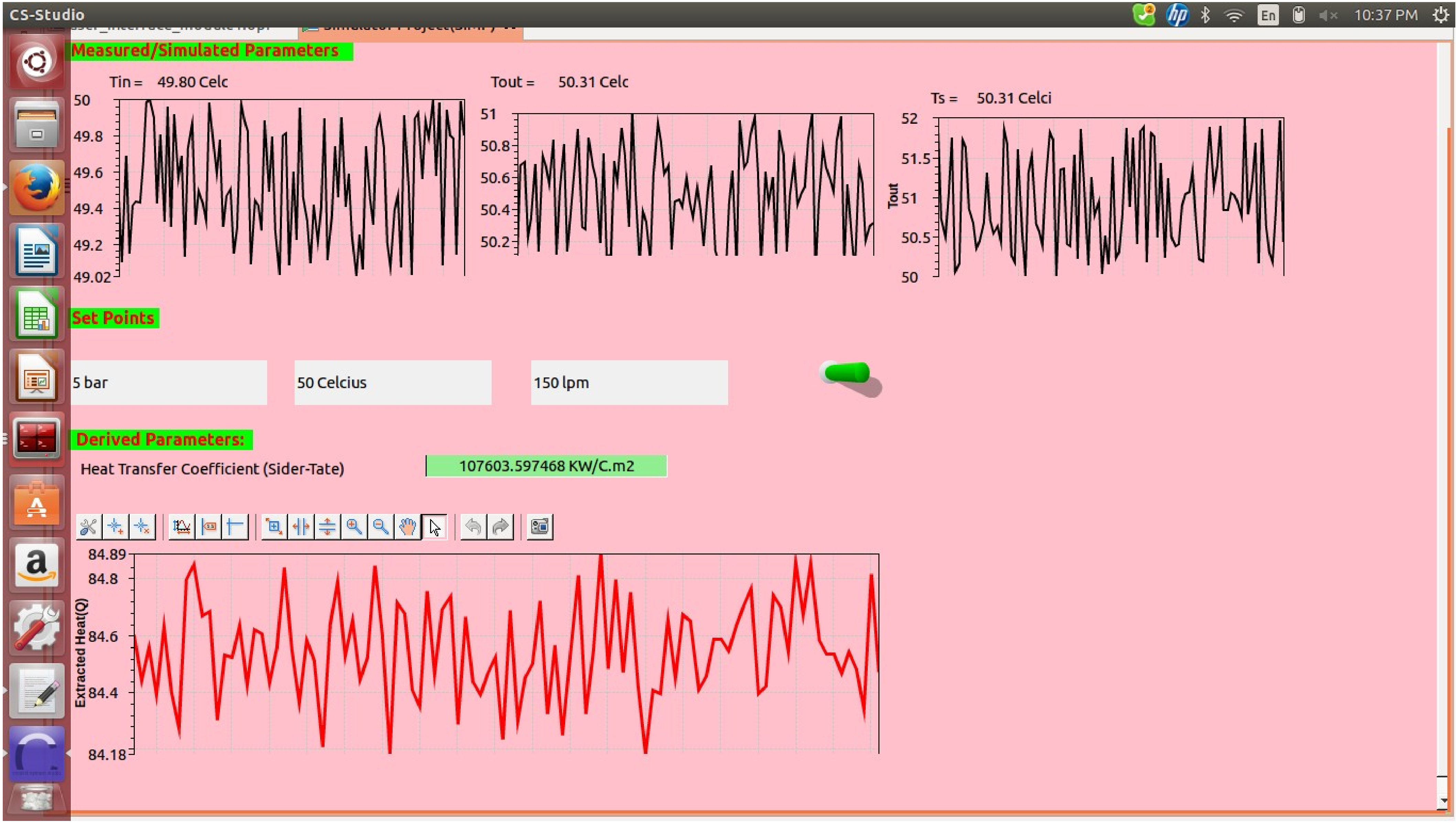


Figure: CHF Optimization and Pattern Visualization

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.

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Thanking you