Saturne: EDF's General Purpose CFD Software

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Code_Saturne®: EDF’s general purpose CFD software

General presentation of Code_Saturne
Numerical simulation at EDF R&D
Simulate and decide

Power generation
- Improvement of efficiency and safety of our facilities
- Optimisation of maintenance and life span
- New generations of power plants
- Innovation in renewable energies and storage
- Response to specific events (flood, heatwave, incidents, ...)

Customers
- Home and building: development of technologies and services for energy efficiency
- Industry: development of energy efficiency and new electric uses

Our world
- Anticipation of climate constraints on shared resources
- Improvement the environmental impact of our facilities
Code development at EDF R&D

- **Code_Saturne**
  - general usage single phase CFD, plus specific physics
  - property of EDF, open source (GPL)
  - http://www.code-saturne.org

- **NEPTUNE_CFD**
  - multiphase CFD, esp. water/steam
  - property of EDF/CEA/AREVA/IRSN (proprietary)

- **SYRTHES**
  - thermal diffusion in solid and radiative transfer
  - property of EDF, open source (GPL)
  - http://rd.edf.com/syrthes

- **Code_Aster**
  - general usage structure mechanics
  - property of EDF, open source (GPL)
  - http://www.code-aster.org
Code development at EDF R&D

- **TELEMAC system**
  - free surface flows
  - proprietary, commercially distributed
  - [http://www.telemacsystem.com](http://www.telemacsystem.com)

- **SALOME platform**
  - integration platform (CAD, meshing, post-processing, code coupling)
  - property of EDF/CEA/OpenCascade, open source (LGPL)
  - [http://www.salome-platform.org](http://www.salome-platform.org)

- **Open TURNS**
  - tool for uncertainty treatment and reliability analysis
  - property of EDF/CEA/Phimeca, open source (LGPL)
  - [http://trac.openturns.org](http://trac.openturns.org)

- and many others
  - neutronics
  - electromagnetism
  - component codes
  - system codes
  - .....
General elements on *Code_Saturne*
**Code_Saturne: main capabilities**

### Physical modelling
- Single-phase laminar and **turbulent flows**: k-ε, k-ω SST, v2f, RSM, LES
- **Radiative** heat transfer (DOM, P-1)
- **Combustion** coal, gas, heavy fuel oil (EBU, pdf, LWP)
- **Electric** arc and Joule effect
- **Lagrangian** module for dispersed particle tracking
- **Atmospheric flows** (aka *Mercure_Saturne*)
- Specific **engineering module** for cooling towers
- **ALE** method for deformable meshes
- **Rotor / stator interaction** for rotating flows
- **Conjugate heat transfer** (SYRTHES & 1D)
- Common structure with NEPTUNE_CFD for **eulerian** multiphase flows

### Flexibility
- **Portability** (UNIX, Linux and MacOS X)
- Standalone **GUI** and integrated in **SALOME** platform
- **Parallel** on distributed memory machines
- **Periodic boundaries** (parallel, arbitrary interfaces)
- Wide range of **unstructured meshes** with arbitrary interfaces
- **Code coupling** capabilities (*Code_Saturne/Code_Saturne*, *Code_Saturne/Code_Aster*, ...)

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Code_Saturne: general features

Technology
- Co-located finite volume, arbitrary unstructured meshes, predictor-corrector method
- 500 000 lines of code, 49% FORTRAN 90, 41% C, 10% Python

Development
- **1998: Prototype** (long time EDF in-house experience, ESTET-ASTRID, N3S, ...)
- **2000: Version 1.0** (basic modelling, wide range of meshes)
- **2001: Validation** for single phase nuclear thermal-hydraulic applications
- **2004: Version 1.1** (complex physics, LES, parallel computing)
- **2006: Version 1.2** (state of the art turbulence models, GUI)
- **2008: Version 1.3** (massively parallel, ALE, code coupling, ...)
  
  Released as open source (GPL licence)
- **2010: Version 2.0** (latest production release, multigrid, atmospheric, cooling towers, code coupling, rotor/stator interaction, easy install & packaging, extended GUI, ...)
- **2011: Version 2.1** (single-packaged with a complete re-writing of memory management, intermediate version partially validated with experimental features like velocity components coupling, BLV2K turbulence model, new combustion model)

Code_Saturne developed under Quality Assurance
Basic software characteristics of \textit{Code\_Saturne}
**Code_Saturne elements**
(from version 2.0)

- **Preprocessor**
  - mesh import
  - mesh pasting
  - periodicity
  - domain decomposition

- **Parallel Kernel**
  - ghost cells creation
  - CFD Solver

- **FVM library**
  - parallel mesh management

- **BFT library**
  - I/O memory management

- **Post-processing**
  - output

- **External libraries (EDF, LGPL):**
  - BFT: Base Functions and Types
  - FVM: Finite Volume Mesh
  - MEI: Mathematical Expression Interpreter

- **GUI**
  - Xml data file

- **MEI library**
  - Mathematical Expression Interpreter

- **Code_Saturne**
  - Meshes

- **Restart files**

- **Code coupling**
  - SYRTHES
  - Code_Aster
  - SALOME platform

- **Parallel treatment**

- **XML data file**

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**Code_Saturne elements**

- **Graphical User Interface**
  - setting up of calculation parameters
  - parameter stored in XML file
  - interactive launch of calculations
  - some specific physics not yet covered by GUI
  - advanced setting up by FORTRAN user routines

- **Integration in the SALOME platform**
  - extension of GUI capabilities
  - mouse selection of boundary zones
  - advanced user files management
  - from CAD to post-processing in one tool
Parallelism

- Classical domain splitting using MPI

PWR lower plenum decomposition (Metis)
Parallelism - periodicity

Parallelism and translation periodicity: data exchange

Initial mesh

| 1 | 3 | 5 | 7 |
| 2 | 4 | 6 | 8 |

Domain partitioning

Mesh

| 1 | 3 | 5 | 7 |
| 2 | 4 | 6 | 8 |

Data exchange

Parallel treatment

Periodicity

Data exchange

Periodic treatment

Rotation periodicity: similar but implementation is more complex

- Vectors and tensors rotation required (component coupling)
**Code_Saturne prerequisite**

**Basic prerequisite**
- C and FORTRAN compilers, standard Python

**Prerequisite for GUI**
- Python with Qt4
- Libxml2

**Prerequisite for parallel computing**
- Metis or Scotch for domain decomposition
  - not mandatory but strongly advised for better load balance
- any MPI library

**Other optional libraries**
- CGNS
- MED, HDF5
- Zlib

**Memory usage**
- approximately 1 GB for 1,000,000 cells (for a standard 3D calculation)
General capabilities of Code_Saturne
Supported meshes

Mesh generators
- I-DEAS, Simail
- GAMBIT, ICEM-CFD
- IGG-HEXA, STAR-CCM+
- SALOME
- Harpoon, GMSH, …

Formats
- Above mentioned mesh generators + MED, CGNS, EnSight Gold…

Cells: arbitrary arrangement of polyhedra of any type
- For example: tetrahedra, hexahedra, prisms, pyramids, n-faced polyhedra, ...

Mesh pasting: « any type of mesh / format » + « any type of mesh / format »
- Meshes may be contained in one single file or in several separate files
- Order of meshes has no influence
- Arbitrary interfaces can be selected by mesh references
- Expertise may be required if arbitrary interfaces are used:
  - in critical regions
  - with LES
  - with very different mesh refinements
  - on curved CAD surfaces
Mesh examples

Example of mesh with stretched cells and hanging nodes

PWR lower plenum

3D polyedral cells

Example of composite mesh

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Advanced post-processing capabilities

- **FVM library capabilities**
  - fully parallel treatment
  - post-processing files written while calculation is running
  - optional discard of non-standard polygons or polyhedra
  - optional tessellation of non-standard polygons or polyhedra → adaptation to format or post-processing tool features

- **User-defined, time dependent, post-processing meshes and variables**
Large Eddy Simulation (unsteady turbulence modelling)

Application example: thermal fatigue
Contrary to classical RANS approaches, Large Eddy Simulation allows to represent the large structures of the flow, and, by thermal coupling with the structure, to determine the wall thermal loading.

Dynamic model (with filter requiring no homogeneous direction)
Wall treatment: refinement with hanging nodes or wall functions
Synthetic turbulence (for inlet and coupling with RANS)
**Arbitrary Lagrangian Eulerian method (ALE)**

- **Deformable meshes**
  - mesh deformation estimated from boundary conditions
  - possibility for the user to specify the movement of any node
  - initially designed for fluid/structure interaction
  - current tests on free surface modelling

Channel flow with two moving cylinders defined as independent structure with internal coupling
(mesh viscosity = 1 (blue) or $10^{10}$ (red))
Thermal fluide-structure interaction

1D wall thermal model
- fully integrated in Code_Saturne
- no transverse thermal diffusion in the solid

SYRTHES open source software
- transient thermal simulations in complex solid geometries
- diffuse and isotropic wall to wall thermal radiation with shadowing effect
- parallel version and GUI under development

Coupling with Code_Saturne
- thermal shocks and wall thermal inertia
- explicit coupling at each time step
- parallel/parallel coupling
- volume coupling under development
Fluid-structure interaction

- **Code_Saturne internal module**
  - basic frictional spring law for non-deformable structures

- **Code_Saturne/Code_Aster coupling**
  - coupling via the SALOME platform
    - based on the YACS coupler module
    - standard implementation in Code_Saturne under validation
    - to be implemented in the standard version of Code_Aster

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Coupling of *Code_Saturne* with itself

**Objective**
- coupling of different models (RANS/LES)
- fluid-structure interaction with large displacement
- rotating machines

**Two kinds of communications**
- data exchange at boundaries for interface coupling
- volume forcing for overlapping regions

**Still under development, but ...**
- data exchange already implemented in FVM library
  - optimised localisation algorithm
  - compliance with parallel/parallel coupling
- prototype versions with promising results
  - more work needed on conservativity at the exchange
- first version adapted to pump modelling implemented in version 2.0
  - rotor/stator coupling
  - compares favourably with CFX
Lagrangian modelling for multi-phase flows

- Generally used to obtain refined statistics on a dispersed phase
- Stochastic modelling with 2-way coupling (momentum, heat, mass)
- Fine particle/wall interaction
  - van der Vaals forces
  - deposition and resuspension

Some applications:
- deposit, slagging and fouling (PWR heat exchangers, coal furnaces …)
- particle trajectories in cyclone separators
- impact phenomena (turbine blades)
Pollutant prediction in Gas Turbine Rio-Bravo 495 MW Turbine

CFD complements or replaces data that turn out to be difficult to obtain

3D computation
- Film cooling, swirled inlet
- EBU combustion model
- Refined chemical analysis
  - In zones defined from T and f

Pollutant prediction (Nox)
Pulverised coal and heavy fuel oil combustion

Nox, slagging and fouling, flame stability, temperature peaks
3D modelling + refined chemical analysis
⇒ optimization of maintenance and performance
Current developments on oxycombustion

Low NOx burner
Atmospheric flows

- Specific models
  - boundary conditions
  - atmospheric boundary layer
  - potential temperature

- Mercure_Saturne derived version
  - based on Code_Saturne
  - still to be transferred in the standard version of Code_Saturne
    - humidity
    - radiative source terms
    - micro-physics and chemistry of pollutants
Electric module: Joule effect

- Use of constant complex potential to account for tri-phase alternating current
- Offset effect accounted for

- Strongly variable physical properties, especially viscosity
- Specific pressure-velocity coupling to support large time steps
Electric arcs applications

Phenomena
- Joule effect and Laplace forces
- Radiative heat transfer
- Breakdown and restriking of arcs

Difficulties
- Strong source terms: 28 MJ on tube 1.7 m long and 10 cm diameter
- Highly unsteady phenomena
- Variable physical properties: temperature from 300 to 30000 K

Applications
- Temperature peak in electric transformers
- Combustion/Vitrification of radioactive waste (medium activity, long life)
- Arc default effect in closed posts
- Lightning striking of airplanes

(EDF/ONERA/CEAT cooperation)

(image Airbus France)
Cooling towers engineering module

- **Plumes**
  - natural convection

- **Fans and packing**
  - turbulence, head losses, forced convection

- **Rain-zones and frost**
  - 2-phase flows with heat and mass transfer
Parallel performances of *Code_Saturne*
High Performance Computing with *Code_Saturne*

*Code_Saturne* used extensively on HPC machines
- in-house EDF clusters
- CCRT calculation centre (CEA based)
- EDF IBM BlueGene machines (8 000 and 32 000 cores)
- MareNostrum supercomputer (Barcelona Computing Centre)
  → intensive work on parallel optimisation

*Code_Saturne* used as reference in PRACE European project
- reference code for CFD benchmarks on 6 large European HPC centres
- *Code_Saturne* awarded “gold medal” in scalability by Daresbury Laboratory (UK, HPCx)
Parallel Performance - FATHER test case

“FATHER” LES case (thermal fatigue in a T-junction)

- 1M cells
- In 2003, a full run required **63 days** using one vector processor on EDF's Fujitsu VPP 5000 computer for ten physical seconds simulated (50 000 iterations).
- In 2004, the same run required **10 days** on 32 processors of an HP AlphaServer (CCRT)
- Now on Blue Gene EDF Machine: would require **less than 1 day** on 512 processors
  
  .... but we don’t do that case anymore!
Current frontier with *Code_Saturne*

- PWR nuclear reactor mixing grid
  - 100 Mcells
  - calculation run on 4,000 to 8,000 cores
  - major lock due to mesh generation
Code_Saturne is open source
**Code_Saturne** open source practical info

- **Distribution of Code_Saturne**
  - GPL licence, auxiliary libraries (BFT, FVM and MEI) under LGPL licence

- **Downloadable versions:**
  - 2.0 fully validated version since summer 2010 (2.0.2 July 2011)
  - 2.1 partially validated version (2.1.0 August 2011)

- **Code_Saturne EDF website**
  - [http://www.code-saturne.org](http://www.code-saturne.org)
  - source download
  - code presentation and documentation
  - contact with EDF development and support team
  - **Code_Saturne** news
  - Forum and bug-tracker

  [https://code-saturne.info/products/code-saturne](https://code-saturne.info/products/code-saturne)
**Code_Saturne open source practical info**

- **University of Manchester TWiki website**
  - http://saturne.cfdtm.org
  - interactive TWiki website
  - personal pages, publications, developments of users
  - information, news, forum
  - **test case database**
  - fully open access (free registration needed for write rights)

- **Contact and support around Code_Saturne**
  - **Code_Saturne forum**: [https://code-saturne.info/products/code-saturne/forums](https://code-saturne.info/products/code-saturne/forums)
  - To open an account on the forum or for private topics: saturne-support@edf.fr
  - **Annual User’s Club meeting** in November/December in Paris (France)
  - To appear in the mailing list → saturne-support@edf.fr
  - Initial training sessions in March and November

- **Integration of external developments**
  - Any useful external contribution welcome
  - For easier licence management, any contribution given for integration will be under EDF’s copyright
  - Contributors will be clearly mentioned in the author’s list
  - **Code_Saturne** is a trademark property of EDF
Quality and trust with Code_Saturne
Quality assurance

- Code_Saturne widely used at EDF and outside
  - 150 EDF users (R&D and engineering)
  - 400 “users” contacts outside EDF
  - Code_Saturne used for all general CFD calculations at EDF
  - Code_Saturne especially used in calculations for Nuclear Authorities
    → code developed under Quality Assurance

- Verification of Code_Saturne
  - before each release is declared “fit for industrial use”
  - around 30 test cases, covering all capabilities of the code
  - academic test cases to industrial configurations
  - 1 to 15 calculations per test case
    → around 1 man.year of work

- Validation of Code_Saturne
  - further validation for specific industrial domains, namely nuclear single phase thermal-hydraulics
**Code_Saturne documentation**

- Available documentation
  - up-to-date English user manual
  - Code_Saturne tutorial
    - five basic test cases
    - step by step solution
  - Theory manual
    - description of basic algorithms
    - partially translated in English
Examples of industrial applications of *Code_Saturne*
Thermal fatigue in mixing zones

**Modelling**
- LES unsteady turbulent modelling in the fluid
- coupling with Syrthes for solid temperature
- thermal fields used as input data for structure mechanics calculations

Temperature in the solid

SYRTHES

Temperature in the fluid

Code_Saturne
Thermal fatigue in mixing zones
Thermal shock on PWR vessel under LOCA

Better prediction of thermal shock in case of loss of coolant accident using 3D simulation instead of 1D experimental correlations.
Fluid/structure interaction

Vibration wear of fuel assemblies

Vibration of tube bundles in Steam Generators

Two-phase cross-flow induced excitation

Single-phase cross-flow induced excitation
Air quality in operating theaters
Surface treatment with plasma torch

powder injection

particules
Surface treatment with plasma torch
Preservation of the Lascaux cave

Aeraulics, thermal and hydric transfers

Salle des Taureaux  Diverticule Axial

Collaboration with French Ministry of Culture