Your Journey in Computational Fluid Dynamics - CFD - and Sustainable Energy with the Green Revolution Energy Converter - GREC

The field of computational fluid dynamics represents one of the most exciting intersections of mathematics, physics, engineering, and computer science. From the elegant mathematics of the Navier-Stokes equations to the practical challenge of optimising revolutionary technologies like the **Green Revolution Energy Converter (GREC)**, CFD offers endless opportunities for study, discovery and impact.

What makes this field special - especially now?

You'll work on problems that truly matter: studying the **GREC technology that converts ANY heat gradient into clean energy**, renewable energy systems research to reduce emissions, optimising, or even modeling climate positive systems to reduce global temperature rise. The mathematical beauty of the underlying physics, combined with the computational challenges of solving complex equations, creates a uniquely rewarding career path with direct impact on humanity's sustainability challenges.

The path forward is challenging but clear:
- Build **strong foundations** in mathematics and physics
- Learn **programming and numerical methods**
- Gain **hands-on experience with CFD** tools like OpenFOAM
- Specialise in **application areas** that excite you - particularly sustainable energy technologies
- **Consider joining revolutionary projects like GREC development** - Never stop **learning and exploring**

Your opportunity with GREC:
As students working on this project, you're not just learning textbook concepts - you're contributing to a truly sustainable technology without any harmful emissions, in the right direction to solve the climate crisis. The **GREC project represents the future of sustainable energy**, where computational fluid dynamics, advanced thermodynamics, and innovative engineering converge to create solutions our world desperately needs.

Whether you pursue this field in industry, academia, or research focused on clean energy, you'll be part of a community working to understand and predict one of nature's most complex phenomena: fluid flow that could transform how humanity generates clean energy.

Your next step? Choose one aspect that interests you most—the mathematics, the physics, the programming, or the sustainable energy applications—and dive deeper. The future of CFD is exceptionally bright, with emerging areas like machine learning-enhanced models, quantum computing applications, exascale computing, and **revolutionary clean energy technologies like GREC** opening new frontiers. There has never been a more exciting— or important— time to enter this field. **Consider how your skills could contribute to GREC development or similar breakthrough technologies.** The journey of understanding fluid dynamics is lifelong, but every step brings new insights and opportunities to make a real difference in creating a sustainable future.

Welcome to the fascinating world of CFD and sustainable energy innovation. The GREC revolution starts with understanding the fundamentals - and that understanding starts with you!

The GREC Sustainable Project Guide to Understanding Fluid Dynamics and CFD

A comprehensive introduction for students considering mathematics, thermodynamics, programming, and computational fluid dynamics featuring the Green Revolution Energy Converter (GREC) - A revolutionary sustainable energy technology

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1. Introduction: Why Fluid Dynamics Matters

Imagine you're watching a Formula 1 car slice through the air, or observing how a jet engine propels an aircraft, or even just watching steam rise from your coffee cup. All of these phenomena are governed by the same fundamental equations we'll explore in this guide.

But what if we told you that these same equations could help with one of humanity's greatest challenges: the transition to a zero-carbon economy, generating clean, sustainable kinetic energy from ANY existing temperature gradients like from the sun, geothermal or even low quality waste heat? No combustion needed! This is exactly what you'll be working on with the **Green Revolution Energy Converter (GREC)** - a revolutionary technology that transforms temperature differences into usable energy.

Computational Fluid Dynamics (CFD) is the science of predicting fluid flow, heat transfer, and related phenomena by solving mathematical equations using computers. It's used in:

- **Aerospace**: Designing aircraft wings and rocket engines
- **Automotive**: Reducing drag and improving fuel efficiency
- **Weather Prediction**: Modeling atmospheric flows
- **Medicine**: Understanding blood flow in arteries

- **Energy**: Optimising wind turbines and combustion engines - **and revolutionary new technologies like GREC**
- **Architecture**: Designing ventilation systems
- **Sustainable Technology**: Developing next-generation safe and clean energy solutions

What makes this field exciting? You combine deep physics understanding with cutting-edge mathematics and powerful computing to solve real-world problems that directly impact society - from climate change mitigation to energy independence.

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2. Case Study: The Green Revolution Energy Converter

A Real-World Application of Everything You'll Learn

Throughout this guide, we'll use the **Green Revolution Energy Converter (GREC)** as our primary example. GREC represents everything exciting about modern CFD and thermodynamics: it's innovative, sustainable, and requires deep understanding of fluid mechanics, heat transfer, and computational modeling.

What is GREC?

The GREC is a novel type of external heat engine grounded in **well-established principles of thermodynamics and heat transfer** —but realised in an entirely new way. Unlike traditional designs, the GREC uses modern control systems to orchestrate a revolving thermal cycle, making it best described as a **digitally controlled Carnot engine in motion**. Its innovative configuration enables efficient heat-to-work conversion in a form that is **scalable, cost-effective**, and offering an **entirely carbon-free** transformative approach to sustainable energy technology.

The Physics Behind GREC

The GREC is built on a simple yet powerful concept: converting heat into mechanical work through controlled air movement. At its core, the GREC operates like a Carnot engine, using an electric motor to shift a sealed volume of air—its **Work Generating Volume (WGV)**—between hot and cold surfaces. This creates pressure and volume changes that produce mechanical work, often significantly exceeding the input energy of the motor. The resulting pressure pulses can be harnessed to drive pistons, turbines, pumps, or generators.

Key GREC Principles: - The larger the volume of air, the more energy - The greater the temperature difference, the more energy

In other words, if you have loads of low quality / low gradient temperature heat then you can convert to mechanical energy by building a large GREC motor, On the other hand, if you have a large temperature gradient you may build a compact smaller GREC motor to get an equal kinetic output — a core advantage of GREC's design - as explained below.

Revolutionary Scale and Performance

In thermodynamic terms, the GREC acts as **“a closed system with a moving boundary”** converting ANY existing temperature gradient into mechanical motion (kinetic energy). Traditional external heat engines are constrained by limited (small) cylinder volumes and limited surface area for heat exchange, which restricts their output and efficiency. The GREC overcomes these restrictions by permitting *very large heat transfer areas* and allowing a *very large sliced Work Generating Volume* - WGV which can benefit from even lower temperature differences and be built very large for much higher power output. This allows the system to harness even modest temperature differences and to scale up significantly for high power applications—making it uniquely suited for low-grade or distributed heat sources.
Built from sustainable, readily available materials, the GREC contains no rare earth metals, no radioactive substances.

Current GREC Research and Development

In Sweden, the University of Linköping has successfully advanced the GREC research with several fully documented projects since 2021 including calculations and simulations of the internal heat transfer mechanisms within the GREC Work Generating Volume (WGV). Linköping University designed and built their own Lab Model v3 and in 2024 they performed repeatable experiments with volume change work. A direct conversion of a temperature gradient to electricity with a linear generator was demonstrated by connecting a simple loudspeaker.

Since autumn 2024 ICAM School of Engineering in Toulouse joined to contribute to the GREC project with valuable research and also consolidating earlier work. **A major breakthrough has been achieved with our custom OpenFOAM development**: we have successfully created a fully working `chtMultiRegionFoam` solver with dynamic temperature boundaries and functional MRF (Multiple Reference Frame) zones directly imported from Blender .stl files. This advanced OpenFOAM implementation replicates and significantly extends the original COMSOL-based thermofluid analysis from the foundational study “Investigation of the internal heat transfer in GREC” by Johan Hagströmer, Mattias Reijm, Oscar Torsteinstrud and Vendela Stenholm (Linköping University, 2022).

Our OpenFOAM development includes sophisticated GREC-specific postprocessing capabilities for pressure/temperature tracking and rotation-based analysis, allowing us to model the periodic heat-driven pressure changes inside closed air-filled systems with unprecedented detail. These combined efforts form the foundation for planning our next intermediate small prototype rated at 50W, which will undergo extensive studies and experiments on the ICAM state-of-the-art DepTH-LAB-platform.

Your Role as Future CFD Engineers

With improved Heat Transfer Coefficient (HTC) understanding, we will be better positioned to dimension a large volume GREC motor. Our recent OpenFOAM development breakthrough - a custom `chtMultiRegionFoam` solver with dynamic temperature boundaries and MRF capabilities - now allows us to model GREC systems with unprecedented accuracy. The equation that calculates the desired GREC power output will appear through detailed CFD analysis. Main variables include: - **Revolving speed** (fluid mechanics) - now accurately modeled with our MRF zones - **Temperature gradient** (thermodynamics) - tracked with our dynamic boundary conditions - **Work generating volume size** (geometry optimisation) - imported directly from Blender .stl files - **Heat Transfer Coefficient (HTC)** (computational fluid dynamics) - calculated with advanced postprocessing tools

This OpenFOAM development replicates and extends the foundational COMSOL analysis from the Linköping University study (2022), allowing us to verify previous results while exploring new design possibilities for solar-heated fin configurations and closed gas-filled system optimisation.

These initiatives promise to refine the GREC technology further, bringing us closer to scalable, emission-free energy solutions.

Why GREC Matters for Your Studies

As you progress through this guide, you'll see how every concept - from the Navier-Stokes equations to OpenFOAM simulations - directly applies to understanding and optimising GREC:

1. **Mathematics**: Modeling the cyclical pressure changes and heat transfer
2. **Thermodynamics**: Understanding the Carnot cycle and efficiency optimisation
3. **Fluid Dynamics**: Analysing air flow between hot and cold reservoirs
4. **Programming**: Simulating complex heat transfer mechanisms
5. **CFD**: Optimising the Work Generating Volume design

This is applied learning at its finest - working on technology that could help solve the climate crisis while mastering the fundamental sciences that govern our world.

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3. The Mathematical Foundation

What Math Do You Need?

Essential Mathematics for CFD:

Vector Calculus: The language of fluid mechanics is vectors and fields. You'll work with:

$$\nabla = \frac{\partial}{\partial x}\mathbf{i} + \frac{\partial}{\partial y}\mathbf{j} + \frac{\partial}{\partial z}\mathbf{k}$$

- **Gradient** $\nabla\phi$: How quickly a quantity changes in space
- **Divergence** $\nabla \cdot \mathbf{v}$: How much flow is expanding at a point
- **Curl** $\nabla \times \mathbf{v}$: How much the fluid is rotating

Real Example: When you see water spiraling down a drain, the curl tells you about that rotation!

Partial Differential Equations (PDEs): Fluid flow is described by PDEs because flow properties change in both space AND time:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial x^2}$$

This equation says: "The acceleration of fluid depends on pressure forces and viscous forces."

Linear Algebra: Modern CFD solves millions of equations simultaneously. Matrix operations become crucial:

$$\mathbf{A}\mathbf{x} = \mathbf{b}$$

where **A** might be a 10 million × 10 million matrix.

Study Path for Mathematics

1. **Calculus I-III**: Master derivatives, integrals, and multivariable calculus
2. **Vector Calculus**: Essential for understanding field equations
3. **Differential Equations**: Both ordinary (ODEs) and partial (PDEs)
4. **Linear Algebra**: Matrix operations and eigenvalue problems
5. **Numerical Analysis**: How to solve equations on computers

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4. Physical Understanding: Thermodynamics

The Physics Behind the Math

Understanding WHY the equations work requires solid thermodynamics knowledge.

The Three Fundamental Laws

- **First Law (Energy Conservation)**:

$$dE = \delta Q - \delta W$$

Energy cannot be created or destroyed. In fluid mechanics, this becomes the energy equation in our Navier-Stokes system.

- **Second Law (Entropy)**:

$$dS \geq \frac{\delta Q}{T}$$

This law determines the direction of natural processes and is crucial for understanding shock waves and turbulence.

- **Third Law**:
  At absolute zero temperature, entropy approaches zero. Less relevant for most CFD applications.

Key Thermodynamic Concepts **Equation of State**: Relates pressure, density, and temperature

$$p = \rho RT$$

For air at room temperature, this tells us that if we compress air (increase ρ), either pressure or temperature must increase.

Specific Heats:
- c_p: Heat capacity at constant pressure
- c_v: Heat capacity at constant volume
- $\gamma = c_p/c_v$: Ratio of specific heats (1.4 for air)

Phase Changes:
Understanding when water becomes steam, or when supersonic flow creates shock waves.

Real-World Connection: GREC and Temperature Gradients

In high-speed flight, such as a jet traveling at Mach 2, air can heat up to over 500 °C purely due to compression—**no external heat source required**. This striking example from thermodynamics shows how pressure and temperature are closely linked in gases.

The GREC applies similar thermodynamic principles, but in a very different way. Instead of compressing air rapidly, it **moves a sealed volume of air (the Work Generating Volume) between hot and cold surfaces**. This controlled temperature cycling causes pressure changes, which are then converted into mechanical work.

Understanding how temperature gradients drive pressure and energy conversion is key to optimising GREC performance. The larger the temperature difference between the hot and cold regions, the more energy the GREC can extract—**a direct application of Carnot cycle principles**.

Study Path for Thermodynamics

1. **Basic Thermodynamics**: Learn the fundamental laws and cycles
2. **Fluid Properties**: Understanding how pressure, temperature, and density relate
3. **Heat Transfer**: Conduction, convection, and radiation
4. **Compressible Flow**: What happens when fluids move very fast
5. **Statistical Mechanics**: For advanced understanding of molecular behavior

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5. The Navier-Stokes Equations Explained

Now let's build up to the full equations step by step, understanding what each term means physically.

Conservation Laws: The Foundation

All of fluid mechanics comes from three conservation principles:

1. Conservation of Mass (Continuity Equation)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

In words: "Mass cannot appear or disappear. If fluid flows out of a region, the mass in that region must decrease."

Physical insight: This is why water speeds up when flowing through a narrow pipe. The mass flow rate $\rho \mathbf{v} \cdot \mathbf{A}$ must be constant, so if area A decreases, velocity v increases.

2. Conservation of Momentum (Newton's Second Law for Fluids)

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p + \nabla \cdot \tau + \rho \mathbf{g}$$

In words: "The rate of change of momentum equals the sum of all forces: pressure forces, viscous forces, and body forces like gravity."

Breaking it down: - $\frac{\partial(\rho \mathbf{v})}{\partial t}$: Local acceleration (things speeding up in time) - $\nabla \cdot (\rho \mathbf{v}\mathbf{v})$: Convective acceleration (things speeding up because they move to faster regions) - $-\nabla p$: Pressure force (fluid moves from high to low pressure) - $\nabla \cdot \tau$: Viscous force (internal friction) - $\rho \mathbf{g}$: Gravity

3. Conservation of Energy for GREC Systems $\frac{\partial(\rho E)}{\partial t} + \nabla \cdot [(\rho E + p)\mathbf{v}] = \nabla \cdot (\mathbf{v} \cdot \tau) + \nabla \cdot (k \nabla T) + \rho \mathbf{g} \cdot \mathbf{v}$

In words: "Energy changes due to work done by pressure and viscous forces, heat conduction, and gravitational work."

GREC Application: In the GREC system, this equation governs how thermal energy from the hot reservoir is converted to mechanical work through pressure changes. The **Work Generating Volume (WGV)** acts as a "closed system with a moving boundary" where energy conservation determines the efficiency of converting temperature gradients into usable power. The heat conduction term $\nabla \cdot (k \nabla T)$ is particularly important for calculating the **Heat Transfer Coefficient (HTC)** that determines GREC performance.

The Complete Compressible Navier-Stokes System

In compact form:

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F}(\mathbf{U}) = \nabla \cdot \mathbf{F}_v(\mathbf{U}, \nabla \mathbf{U}) + \mathbf{S}$$

where:

$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho \mathbf{v} \\ \rho u \mathbf{v} + p\mathbf{e}_x \\ \rho v \mathbf{v} + p\mathbf{e}_y \\ \rho w \mathbf{v} + p\mathbf{e}_z \\ (\rho E + p)\mathbf{v} \end{pmatrix}$$

Key Physical Parameters for GREC Analysis

Reynolds Number: $Re = \frac{\rho V L}{\mu} = \frac{\text{inertial forces}}{\text{viscous forces}}$

- **Low Re ($<$ 1)**: Viscous flow, smooth and predictable (honey flowing)
- **High Re ($>$ 4000)**: Turbulent flow, chaotic and mixing (air around a car)

GREC Application: The air flow in GREC's Work Generating Volume operates in different Reynolds number regimes depending on the **revolving speed**. Understanding this helps optimise the cycling frequency for maximum power output.

Mach Number: $Ma = \frac{V}{a} = \frac{\text{flow speed}}{\text{sound speed}}$

- **Ma $<$ 0.3**: Incompressible flow (water in pipes)
- **Ma $>$ 1**: Supersonic flow (jet engines, shock waves)

Prandtl Number: $Pr = \frac{\mu c_p}{k} = \frac{\text{momentum diffusion}}{\text{thermal diffusion}}$

GREC Critical Parameter: This tells us how heat and momentum spread at different rates. For GREC's **Heat Transfer Coefficient (HTC)** calculations, the Prandtl number determines how efficiently thermal energy transfers from the hot reservoir to the working fluid, directly affecting GREC's power output equation.

Viscous Stress: Internal Friction

The viscous stress tensor captures internal friction:

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k} \right)$$

Physical meaning: Layers of fluid moving at different speeds create shear stress, just like sliding two sheets of paper past each other.

Temperature Dependence: Sutherland's Law

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + S}{T + S}$$

Viscosity changes with temperature! Hot air is less viscous than cold air, which affects everything from weather patterns to engine performance.

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6. Programming and Numerical Methods

Why Programming is Essential

The Navier-Stokes equations are so complex that analytical solutions exist only for very simple cases. For real problems, we need computers.

Python for CFD: Getting Started

Essential Libraries

```
import numpy as np          # Numerical arrays and operations
import scipy.sparse as sp   # Sparse matrices for large systems
import matplotlib.pyplot as plt  # Visualization
import numba                # Just-in-time compilation for speed
```

GREC Heat Transfer Simulation Example Here's how you might simulate heat transfer in a GREC-like system:

```
import numpy as np
import matplotlib.pyplot as plt

def grec_heat_transfer_simulation(nx=100, nt=2000, T_hot=400, T_cold=300):
    """
    Simulate heat transfer in GREC Work Generating Volume
    Models temperature distribution as air moves between hot and cold reservoirs
    """
    # Grid setup
    dx = 1.0 / (nx - 1)
    dt = 0.0001
    alpha = 0.01  # Thermal diffusivity

    # Initialize temperature field
    T = np.ones(nx) * T_cold

    # Simulate GREC cycle
    cycle_results = []

    for cycle in range(10):  # 10 GREC cycles
        # Phase 1: Exposure to hot reservoir
        T[0:int(0.3*nx)] = T_hot

        for n in range(nt//10):
            Tn = T.copy()
            # Heat diffusion equation
            T[1:-1] = Tn[1:-1] + alpha * dt/dx**2 * (Tn[2:] - 2*Tn[1:-1] + Tn[:-2])

        # Calculate work potential (pressure change due to temperature)
        work_potential = np.sum(T - T_cold) * dx  # Simplified work calculation
        cycle_results.append(work_potential)

        # Phase 2: Exposure to cold reservoir
```

```
        T[0:int(0.3*nx)] = T_cold

        for n in range(nt//10):
            Tn = T.copy()
            T[1:-1] = Tn[1:-1] + alpha * dt/dx**2 * (Tn[2:] - 2*Tn[1:-1] + Tn[:-2])

    return T, cycle_results

# Run GREC simulation
final_temp, work_cycles = grec_heat_transfer_simulation()

plt.figure(figsize=(12, 5))

plt.subplot(1, 2, 1)
plt.plot(final_temp)
plt.title('Temperature Distribution in GREC Work Generating Volume')
plt.xlabel('Position')
plt.ylabel('Temperature (K)')

plt.subplot(1, 2, 2)
plt.plot(work_cycles, 'o-')
plt.title('Work Potential per GREC Cycle')
plt.xlabel('Cycle Number')
plt.ylabel('Work Potential (arbitrary units)')

plt.tight_layout()
plt.show()

print(f"Average work per cycle: {np.mean(work_cycles):.2f}")
```

This simulation demonstrates key GREC principles:

- How temperature gradients drive energy conversion
- The cyclic nature of GREC operation
- How **Work Generating Volume size** affects energy output
- The importance of Heat Transfer Coefficients in determining efficiency

Numerical Methods Fundamentals

Discretisation: From Continuous to Discrete **Finite Differences**: Replace derivatives with differences

$$\frac{\partial u}{\partial x} \approx \frac{u_{i+1} - u_{i-1}}{2\Delta x}$$

Finite Volumes: Ensure conservation by working with cell averages

$$\int_V \frac{\partial u}{\partial t} dV + \oint_S \mathbf{F} \cdot \mathbf{n} dS = \int_V S dV$$

Finite Elements: Use basis functions to approximate the solution

$$u(\mathbf{x}) \approx \sum_{i=1}^{N} U_i \phi_i(\mathbf{x})$$

Time Integration **Explicit Methods** (easier but limited by stability):

$$u^{n+1} = u^n + \Delta t \cdot f(u^n)$$

Implicit Methods (more stable but require solving equations):

$$u^{n+1} = u^n + \Delta t \cdot f(u^{n+1})$$

The CFL Condition For numerical stability:

$$\Delta t \leq C_{CFL} \min\left(\frac{\Delta x}{|u| + a}, \frac{\Delta x^2 \nu}{2}\right)$$

This says information cannot travel more than one grid cell per time step.

Advanced Python Concepts for CFD

Vectorisation for Performance

```
# Slow (loops)
for i in range(1, nx-1):
    u_new[i] = u[i] + dt/dx**2 * (u[i+1] - 2*u[i] + u[i-1])

# Fast (vectorized)
u_new[1:-1] = u[1:-1] + dt/dx**2 * (u[2:] - 2*u[1:-1] + u[:-2])
```

Sparse Matrices for Large Systems

```
from scipy.sparse import diags
from scipy.sparse.linalg import spsolve

# Create tridiagonal matrix for 1D Laplacian
A = diags([-1, 2, -1], [-1, 0, 1], shape=(nx, nx)) / dx**2
```

Study Path for Programming

1. **Python Basics**: Variables, functions, control structures
2. **NumPy**: Array operations and linear algebra
3. **SciPy**: Scientific computing tools
4. **Matplotlib**: Data visualisation
5. **Object-Oriented Programming**: Organising complex CFD codes
6. **Parallel Programming**: Using multiple cores for large simulations
7. **Profiling and Optimisation**: Making code run faster

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7. Introduction to OpenFOAM

What is OpenFOAM?

OpenFOAM (Open-source Field Operation And Manipulation) is the world's leading free CFD software. It's used by:
- Boeing and Airbus for aircraft design
- Formula 1 teams for aerodynamics
- Universities for research
- Small companies that can't afford expensive commercial software

Why OpenFOAM Matters

Advantages:
- **Free and open-source**: You can modify the source code
- **Industrial strength**: Used for real engineering projects
- **Highly parallel**: Runs efficiently on supercomputers
- **Extensive physics**: Turbulence, combustion, multiphase flow, etc.
- **Active community**: Continuous development and support

Learning curve: Steeper than commercial software, but much more flexible and powerful once mastered.

OpenFOAM Structure

Case Directory Structure

```
myCase/
   0/           # Initial conditions
      U        # Velocity field
      p        # Pressure field
      T        # Temperature field
   constant/    # Physical properties
      transportProperties
   system/      # Numerical settings
      controlDict
      fvSchemes
      fvSolution
   results/     # Output data
```

Example: GREC Heat Transfer Analysis GREC Temperature Field (0/T):

```
dimensions      [0 0 0 1 0 0 0];  // Temperature in Kelvin

internalField   uniform 350;      // Initial WGV temperature

boundaryField
{
    hotReservoir
    {
        type            fixedValue;
```

```
        value           uniform 400;  // Hot side temperature
    }

    coldReservoir
    {
        type            fixedValue;
        value           uniform 300;  // Cold side temperature
    }

    movingBoundary
    {
        type            movingWallTemperature;  // GREC's moving boundary
        velocity        uniform (0.5 0 0);     // Controlled by electric motor
    }
}
```

GREC Transport Properties (constant/thermophysicalProperties):

```
thermoType
{
    type            heRhoThermo;
    mixture         pureMixture;
    transport       sutherland;
    thermo          hConst;
    equationOfState perfectGas;
    specie          specie;
    energy          sensibleEnthalpy;
}

// Properties for GREC working fluid (air)
mixture
{
    specie
    {
        molWeight       28.9;        // Air molecular weight
    }

    thermodynamics
    {
        Cp              1005;        // Specific heat at constant pressure
        Hf              0;           // Heat of formation
    }

    transport
    {
        mu              1.8e-05;     // Dynamic viscosity
        Pr              0.7;         // Prandtl number (critical for HTC)
    }
}
```

Advanced OpenFOAM Development for GREC Our latest breakthrough: We have developed a fully working `chtMultiRegionFoam` solver with dynamic temperature boundaries specifically for GREC analysis. This custom implementation includes:

- **Dynamic temperature boundaries** that simulate GREC's moving Work Generating Volume
- **Functional MRF (Multiple Reference Frame) zones** directly imported from Blender .stl files
- **GREC-specific postprocessing tools** for pressure/temperature tracking and rotation-based analysis

This advanced OpenFOAM development replicates and extends the original COMSOL-based thermofluid analysis from "Investigation of the internal heat transfer in GREC" by Johan Hagströmer, Mattias Reijm, Oscar Torsteinstrud and Vendela Stenholm (Linköping University, 2022). The original study models periodic heat-driven pressure changes inside closed air-filled systems using solar-heated fins - our OpenFOAM implementation now allows for much more detailed analysis of these complex thermodynamic cycles.

Running Advanced GREC OpenFOAM Simulations

```
# Generate complex GREC geometry from Blender .stl files
surfaceFeatures
snappyHexMesh -overwrite

# Initialize GREC thermal field with dynamic boundaries
setFields -dict system/setFieldsDict.grec

# Run our custom conjugate heat transfer solver for GREC
chtMultiRegionFoam -postProcess -func 'grecPressureTracking'

# GREC-specific postprocessing for rotation analysis
postProcess -func 'grecRotationalAnalysis'
postProcess -func 'grecTemperatureTracking'

# Visualize GREC cycle dynamics
paraFoam
```

Solvers in OpenFOAM for GREC Applications

Heat Transfer Analysis: `chtMultiRegionFoam`, `buoyantSimpleFoam`
Incompressible flow: `simpleFoam`, `pimpleFoam`
Compressible flow: `rhoCentralFoam`, `sonicFoam`
Multiphase: `interFoam`, `multiphaseEulerFoam`
Combustion: `reactingFoam`, `fireFoam`
Turbomachinery: `MRFSimpleFoam`

For GREC Development: Our custom `chtMultiRegionFoam` solver with dynamic temperature boundaries is specifically designed for GREC analysis. The advanced MRF capabilities allow us to model the complex rotational dynamics of GREC's Work Generating Volume, while our specialised postprocessing tools track the critical pressure and temperature cycles that determine power output. This represents a major advancement over the original COMSOL-based analysis, providing much more detailed insights into GREC's heat transfer mechanisms.

Programming with OpenFOAM

OpenFOAM uses C++ with a special syntax that looks almost like mathematical equations:

```
// Solve the momentum equation
fvVectorMatrix UEqn
(
    fvm::ddt(U)
  + fvm::div(phi, U)
  + turbulence->divDevReff(U)
 ==
    fvc::reconstruct
    (
        (
          - ghf*fvc::snGrad(rhok)
          - fvc::snGrad(p_rgh)
        )*mesh.magSf()
    )
);

solve(UEqn == -fvc::grad(p));
```

This code literally says: "Solve the equation: U/ t + · (U) + · = - p + g"

Learning Path for OpenFOAM

1. **Linux Basics**: OpenFOAM runs primarily on Linux
2. **CFD Theory**: Understanding the physics behind the solvers
3. **OpenFOAM Tutorials**: Work through the official tutorials
4. **Mesh Generation**: Learning tools like `blockMesh`, `snappyHexMesh`
5. **Post-processing**: Using ParaView for visualisation
6. **Custom Solvers**: Modifying existing solvers or creating new ones
7. **Parallel Computing**: Running large cases on clusters

8, Career Paths and Study Recommendations

Career Opportunities

Clean Energy and Sustainability CFD is central to developing tomorrow's green technologies:

- New technologies like the **Green Revolution Energy Converter (GREC)**
- **Heat recovery** systems and **waste-to-energy conversion**
- **Geothermal energy optimisation**
- **Thermal energy storage systems design**

- **District heating and cooling networks**

Typical roles: Clean energy engineer, sustainability consultant, R&D specialist, CFD analyst / engineer
Key employers: Vattenfall (SE), Fortum (FI), Climeon (SE), EDF (FR), Veolia (FR), ABB (CH), Siemens Energy (DE), Ørsted (DK)
Why it matters: Contribute to a sustainable future and mitigate climate challenges using advanced simulation tools and cutting-edge technology
Typical salary range: €45,000–€85,000+ (grows with experience and specialisation)

Aerospace and Defense
Simulation is crucial for aerodynamics, propulsion, and thermal systems.

- Aircraft & UAV design (Airbus, Saab, Leonardo)
- Rocket engines and space vehicles (ESA, ArianeGroup, OHB)
- Defense applications (thermal protection, fluid-structure interaction)

Typical roles: Aerodynamics engineer, CFD researcher, propulsion analyst
Key employers: Airbus (DE/FR/ES), Saab (SE), ESA (EU), GKN Aerospace (SE), Avio (IT)
Typical salary range: €50,000–€100,000+

Automotive and E-Mobility
Optimising efficiency, comfort, and emissions through simulation:

- Vehicle aerodynamics (Ford, GM, Tesla, Mercedes)
- Battery thermal management and motor cooling (EV systems)
- Cabin HVAC systems and occupant comfort modeling

Typical roles: Thermal systems engineer, powertrain CFD engineer
Key employers: Volvo (SE), Scania (SE), Porsche Engineering (DE), Renault Group (FR)
Salary range: €45,000–€90,000+

Wind, Nuclear & Process Industry
Fluid-thermal modeling in critical infrastructure:

- **Wind turbine design** (Vestas, Siemens Gamesa, OX2, GE)
- **Nuclear thermal hydraulics** (Vattenfall, EDF, Fortum)
- **Process plant optimisation** (Stora Enso, Yara, BASF)

Typical roles: CFD simulation specialist, thermal analyst
Salary range: €50,000–€95,000+

Technology, Software and Consulting
Simulation experts are in high demand across sectors:

- CFD software companies (NUMECA, ESI, Siemens Simcenter, ANSYS)
- Engineering consulting (AFRY, COWI, DNV, TNO, Fraunhofer)
- **Clean tech startups and R&D** units like the GREC project

Typical roles: Application engineer, consultant, developer
Salary range: €50,000–€100,000+

Academic and Research Paths

- **PhD programs** in Mechanical, Energy or Aerospace Engineering across Europe (e.g., LTH, KTH, Chalmers, LiU, DTU, ETH Zürich, TU Delft, Politecnico di Milano, TU Munich)
- **National laboratories**: (many working on sustainable energy)
- **University-based research groups** advancing numerical methods, turbulence modeling, and sustainable energy systems (GREC case e.g., LTH Lund, LiU Linköping, ICAM Toulouse)
- **EU-funded consortia and international projects**: possible GREC project oportunities between University of Linköping (Sweden), LTH University of Lund (Sweden) and ICAM School of Engineering (Toulouse)
- **Research institutes**: SINTEF (NO), RISE (SE), Fraunhofer (DE), CEA (FR), VTT (FI)

Study Recommendations

Undergraduate Preparation Core subjects:
- Calculus I–III, Differential Equations, Linear Algebra
- Classical Mechanics, Thermodynamics
- Programming (Python, MATLAB, C++)
- Fluid Mechanics, Heat Transfer

Suggested degrees:
1. **Mechanical Engineering** – Strong base for energy, automotive, process industry
2. **Energy Systems Engineering** – Increasingly popular across Europe
3. **Aerospace Engineering** - Aerodynamics, propulsion, control
4. **Engineering Physics** – Strong foundation for simulations and research
5. **Applied Mathematics + CS** – Ideal for those focusing on code and models

Graduate Studies (Master's or PhD) Focus Areas:
- CFD, turbulence, multiphase flows, heat transfer
- Renewable and thermal energy systems
- Advanced numerics and high-performance computing (HPC)
- Fluid-structure interaction, thermal stress modeling
- Machine learning in CFD
- Novel energy technologies (like the GREC)

Where to study (selected top EU/Scandinavian programs):
KTH Royal Institute of Technology (SE) – Energy & CFD focus
LTH Lund Institute of Technology (SE) – Energy Transition & Sustainable CFD
Li.U Linköping University, Institute of Technology (SE) - Applied Thermodynamics and Fluid Mechanics
DTU (DK), **NTNU** (NO), **Chalmers** (SE), **TUM** (DE), **TU** Delft (NL), Politecnico di Torino/Milano (IT), **ICAM** (FR), École Polytechnique (FR)

Building Your CFD Skills

Years 1-2 (Foundation)

- Master vector calculus, differential equations
- Learn Python + MATLAB or C++
- Build physics intuition (thermodynamics, fluid mechanics)
- Practice structured problem-solving (mechanical, physics, math)

Years 3-4 (Specialisation)

- Take advanced courses in heat transfer and fluid dynamics
- Study numerical methods and discretisation of PDEs
- Use OpenFOAM and/or ANSYS Fluent
- Join research projects or internships (local labs, industry partners)

Graduate Level

- Deepen specialisation (energy, aerodynamics, etc.)
- Learn advanced turbulence models and HPC techniques
- Attend CFD conferences and network in the field (e.g., ECCOMAS, Eurotherm, Svenska Mekanikdagarna)
- Consider contributing to OpenFOAM or research repositories

Practical Next Steps

This Week

- Install Python3 and complete beginner NumPy tutorials
- Explore GREC and its principles (closed systems with moving boundaries, www.nilsinside.com)
- Watch CFD videos from European research groups or universities, YouTube channels
- Download and explore OpenFOAM tutorials

Next 6 Months

- Strengthen math vector calculus, differential equations and physics fundamentals
- Learn scientific Python: NumPy, SciPy, Matplotlib
- Read about Reynolds numbers, boundary layers, heat transfer in basic CFD textbooks (see below)
- Follow GREC research updates from Linköping (SE) and ICAM Toulouse (FR), (see below)
- Connect with researchers on LinkedIn or join forums like CFD Online, , follow researchers on social media

2-4 Years

- Specialise based on interest and career goals and build a CFD portfolio
- Apply to internships or master's theses at relevant companies
- Prepare for graduate studies If research interests you or full-time CFD roles in the energy or aerospace sectors

Resources for Continued Learning

Books

- **“Computational Fluid Dynamics” by John Anderson**: Excellent introduction
- **“Numerical Heat Transfer and Fluid Flow” by Patankar**: Classic numerical methods
- **“Turbulent Flows” by Stephen Pope**: Advanced turbulence theory
- **“The OpenFOAM User Guide”**: Essential for OpenFOAM work

Online Platforms / Resources

- **CFD Online** – Forums, tips, project discussions
- **OpenFOAM Wiki** – Case studies and tutorials
- **Coursera / edX** – Numerical methods, CFD, energy systems
- **NASA CFD Resources** - High-quality educational materials
- **GREC reports** - theoretical research, construction, building, and experiments with the GREC Lab Models:

  Theoretical Proof Of Concept For The Green Revolution Energy Converter *Development of a mathematical model, material analysis and physical model improvements* (03/2022) M. Eriksson, O. Magnusson, L. Haglund, J. Malmdal, G. Edholm
  Download: https://www.nilsinside.com/nilsinside/BREC_V2/Development_Of_The_Green_Revolution_Energy_Converter.pdf

  Investigation of the internal heat transfer in GREC – *TMPE09 - Project Report* (12/2022) J. Hagströmmer, M. Reijm, O. Torsteinsrud, V. Stenholm
  Download: https://www.nilsinside.com/nilsinside/BREC_V2/Green-Revolution-Energy-Converter-IHT.pdf

  A study on the heat transfer within the GREC in regards of temperature distribution and heat rate *Thermal Investigation of the Green Revolution Energy Converter* (01/2023) E. Andersson, E. Gustafsson, M. Abrahamsson Bolstad, M. Eriksson, W. Fager
  Download: https://nilsinside.com/nilsinside/BREC_V2/Green-Revolution-Energy-Converter-EHT.pdf

  Design and development of a working prototype for the Green Revolution Energy Converter - Lab model V.3 *Bachelor’s thesis in mechanical engineering* (06/2023) A. Toader, I. Hellström, S. Sandström
  Download: https://nilsinside.com/nilsinside/BREC_V2/GREC_10_1_rapport.pdf

  Development of a mechatronic solution for a new type of heat engine *The selection of relevant electronic components and control system for the mechatronics for the lab model of the new heat engine the Green Revolution Energy Converter - Bachelors thesis* (06/2023) O. Brodin, L. Vilhemsson, M. Hollsten

Download: https://nilsinside.com/nilsinside/BREC_V2/GREC_10_2_rapport.pdf

The thermodynamics of the GREC version 3 - *Investigation of engine performance and energy conversion - Bachelor's theses in mechanical engineering* (06/2023) J. Åsmo, J. Ross, V. Jeirud
Download: https://nilsinside.com/nilsinside/BREC_V2/GREC_10_3_rapport.pdf

Further development of the Green Revolution Energy Converter *Investigating improved control method, sealing and overall performance of LabModel v3, Department of Management and Engineering Bachelor's thesis* (05/2024) E. Widström, R. Zetterman, S. Eriksson
Download: https://www.nilsinside.com/nilsinside/BREC_V2/TMMT31_01_rapport.pdf

GREC Presentation *English Translation from French* (12/2025) M. Peyrony-Rapatout, P. Le Provost
Download: https://nilsinside.com/nilsinside/BREC_V2/2025-01-14-GREC_Final_GREC_Presentation_%20ICAM_Eng.pdf

European Professional Networks

- **ECCOMAS** – European Community on Computational Methods in Applied Sciences
- **Eurotherm** Committee – Heat transfer research
- **Svenska Mekanikdagarna** – Swedish mechanics conference
- **ASME / IACM** – Still relevant globally for CFD practitioners

International Professional Networks

- **American Institute of Aeronautics and Astronautics (AIAA)**
- **American Society of Mechanical Engineers (ASME)**
- **International Association for Computational Mechanics (IACM)**

Conclusion: Your Journey in CFD and GREC

The field of computational fluid dynamics represents one of the most exciting intersections of mathematics, physics, engineering, and computer science. From the mathematics of the Navier-Stokes equations to the practical challenge of optimising compressible and incomressible flows and heat transfer in the Green Revolution Energy Converter, CFD offers endless opportunities for discovery and impact.

What makes this field special?

You'll work on problems that matter: designing more efficient aircraft to reduce emissions, developing better wind turbines for clean energy, optimising GREC applications, or even modeling blood flow to save lives. The mathematical beauty of the underlying physics combined with the computational challenges of solving complex equations creates a uniquely rewarding career path.

The path forward is challenging but clear: - Build strong foundations in mathematics and physics - Learn programming and numerical methods - Gain hands-on experience with CFD tools like OpenFOAM - Specialise in application areas that excite you - Never stop learning and exploring!

Whether you pursue this field in industry, academia, or research, you'll be part of a community working to understand and predict one of nature's most complex phenomena: fluid flow and heat transfer. The equations we've explored here have guided the design of every aircraft, optimised every engine, and helped predict every weather forecast.

Your next step? Choose one aspect that interests you most—the mathematics, the physics, the programming, or the applications—and dive deeper. The journey of understanding fluid dynamics is lifelong, but every step brings new insights and opportunities to make a real difference in the world.

The future of CFD is bright, with emerging areas like machine learning-enhanced turbulence models, quantum computing applications, and exascale computing opening new frontiers. There has never been a more exciting time to enter this field.

Welcome to the fascinating world of computational fluid dynamics!