Development of intellectual approaches for control and design in energy industry

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Benefits of analysing combustion and heat transfer

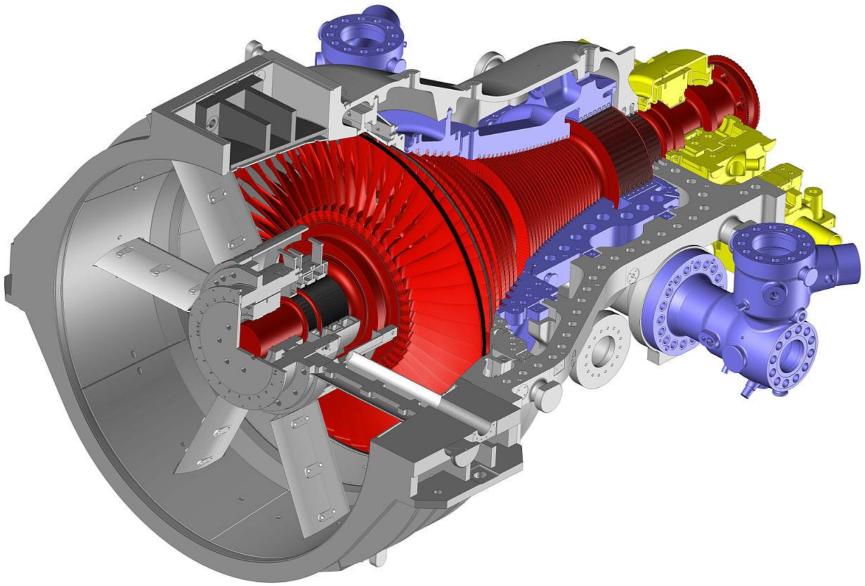
Combustion and heat transfer related applications:

- Transportation
- Electrical power production
- Heating

Combustion and heat transfer analysis can be used for economic as well as environmental benefits by:

- Optimizing fuel economy
- Improving performance and reliability
- Reducing pollutant emissions

Main goal



Modern energy devices must be:

- ✓ Energy efficient
- ✓ Environmentally friendly
- ✓ Safe

The main purpose of this research is to develop intelligent approaches to modernize energy devices such as heat transfer devices, open burners and gas-turbines

Procedure of development

Modernization process

Original devices → I step → II step → III step → Modern devices

- Heat exchanger
- Open burner and combustion chamber
- Gas turbine

USE

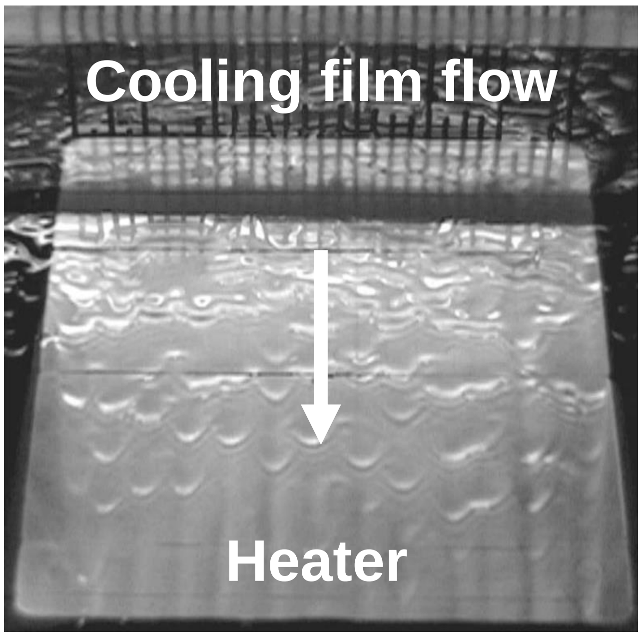
Technologies for flow control:

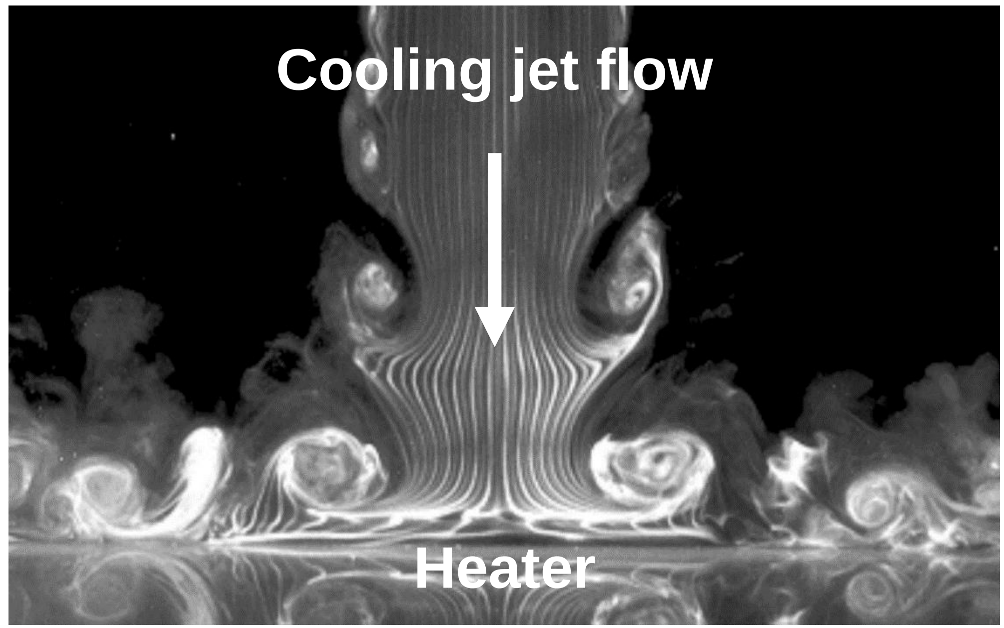
- Swirl
- Periodical forcing
- Device geometry
- Composition of hydrocarbon mixtures

Comments: The process of developing new approaches to modernize original energy devices consists of three main stages. Initially, we have the original devices: model heat exchanger, open burner and combustion chamber and gas turbine with the ability of flow control via swirl, forcing, changing geometry etc.

Original devices: Heat exchanger

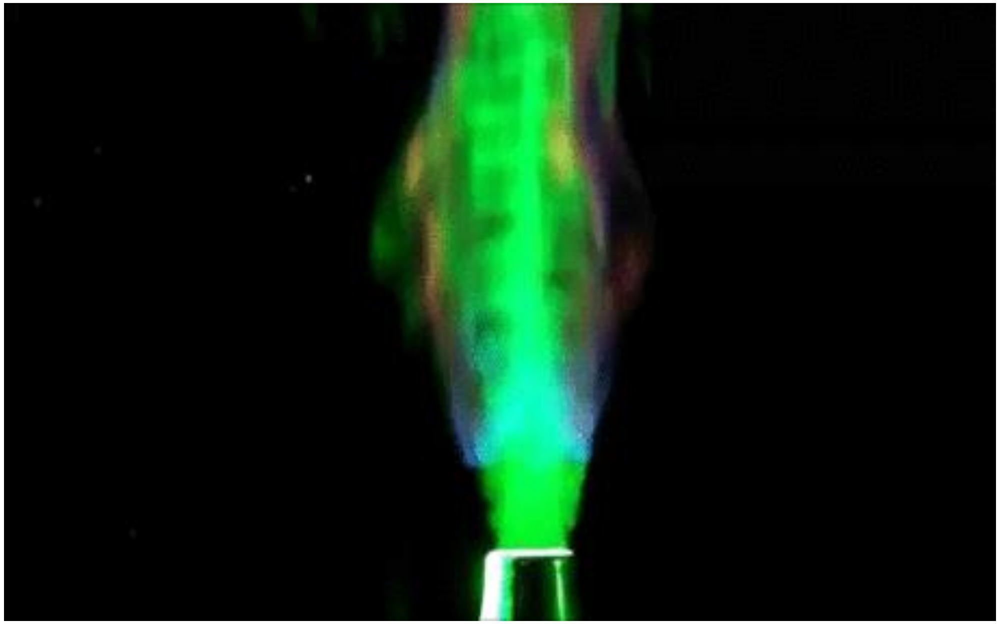
Heat exchanger with water film flow or impact jet cooling

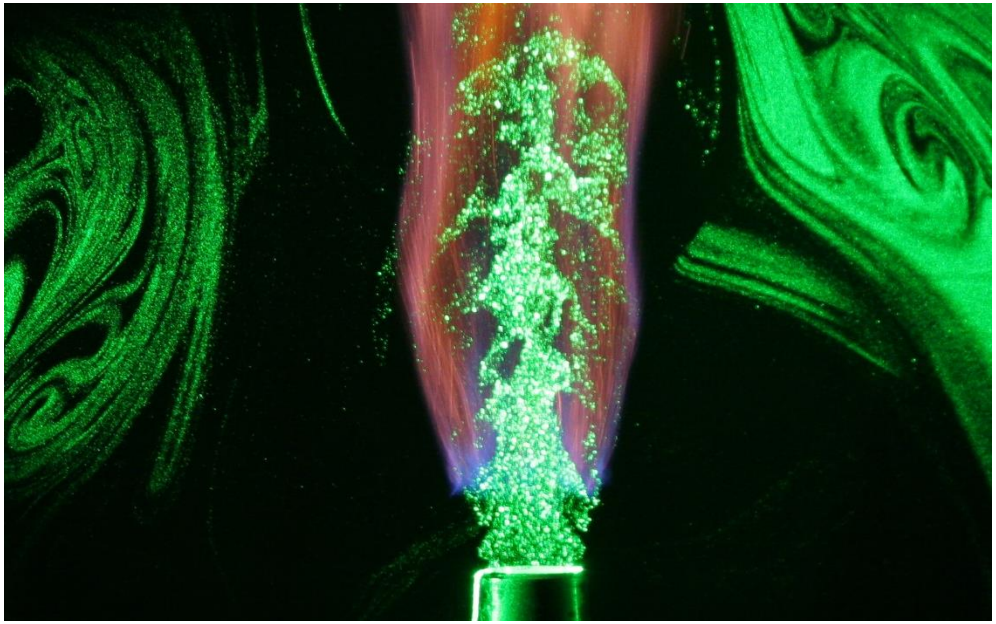




Original devices: Open burner and combustion chamber

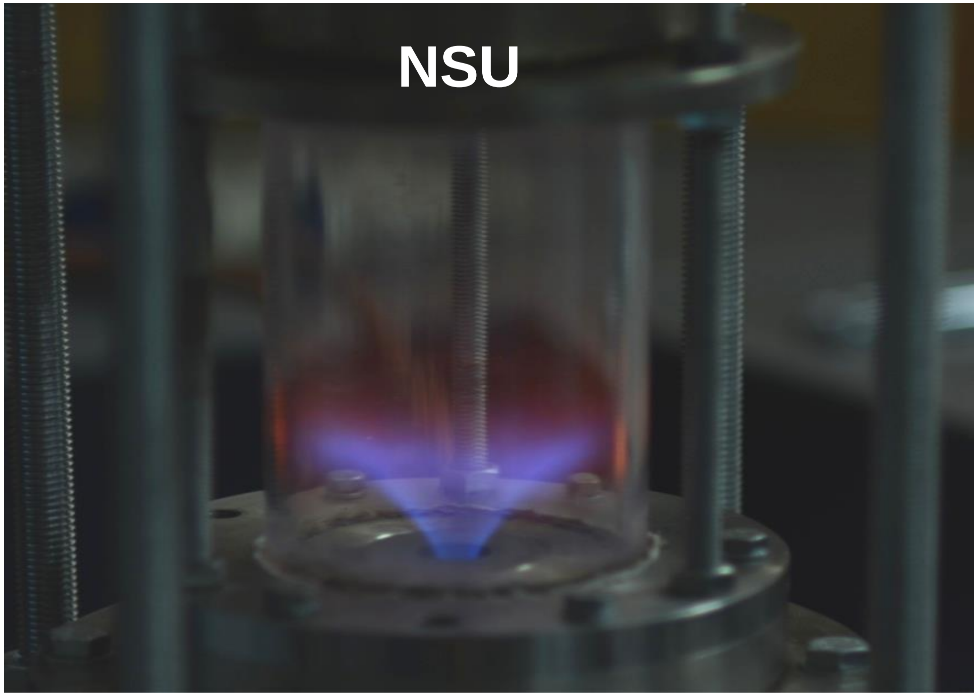
Open burner and combustion chamber working with premixed methane-air and propane-air flames





Original devices: Gas-turbine device

Pressurized gas turbine working with hydrocarbons methane-air and propane-air flames



Procedure of development

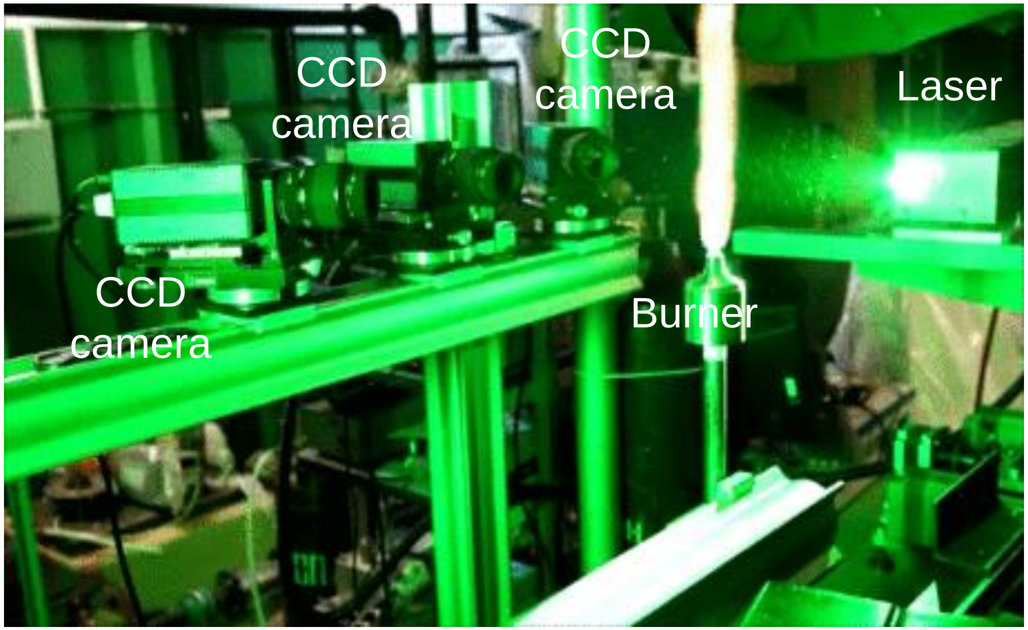
Experimental methods:

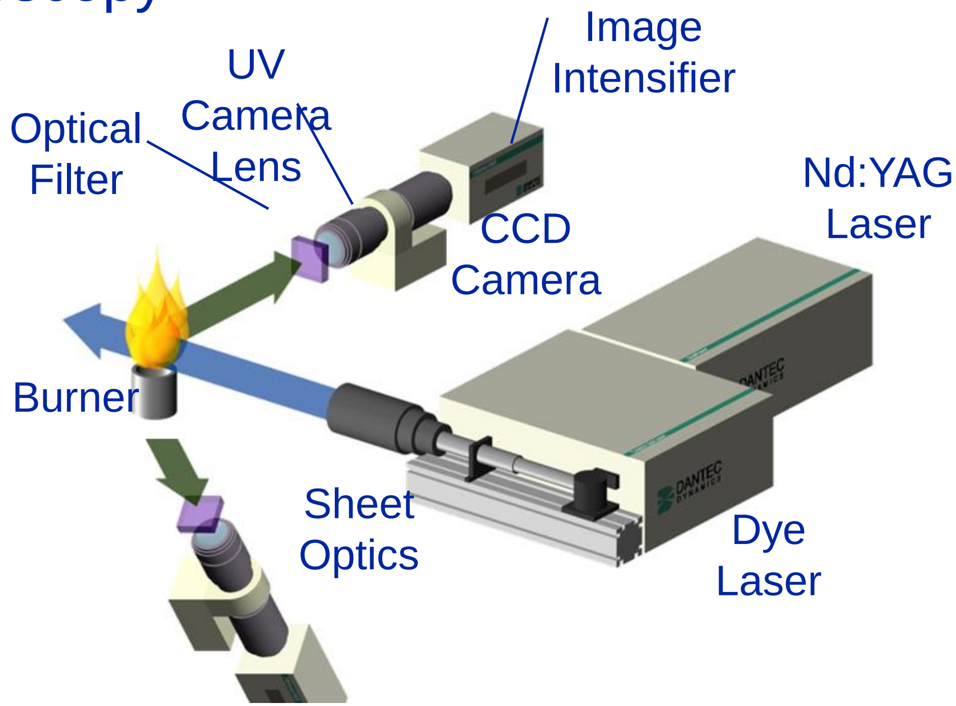
- Particle Image Velocimetry
- Laser Induced Florescence
- Raman Spectroscopy

Comments: In the next step we apply optical methods for diagnostic processes in ordinary devices with the use of control approaches: swirl, forcing etc. Laser-based measurements techniques can provide information on species concentrations, temperature fields, flow velocities etc. and the measurements often have the following properties: 1) Non-intrusive 2) High spatial resolution 3) High temporal resolution 4) High sensitivity 5) Species selective 6) 2D measurements

Optical diagnostic of processes

Combined Particle Image Velocimetry, Laser Induced Fluorescence, Raman Spectroscopy measuring system

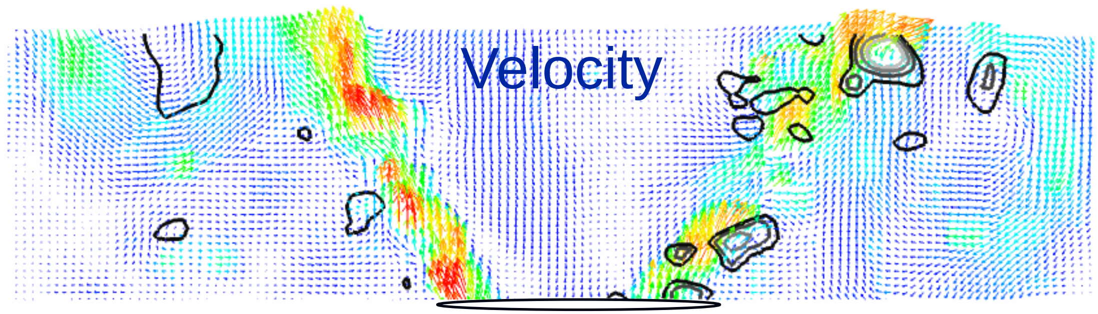




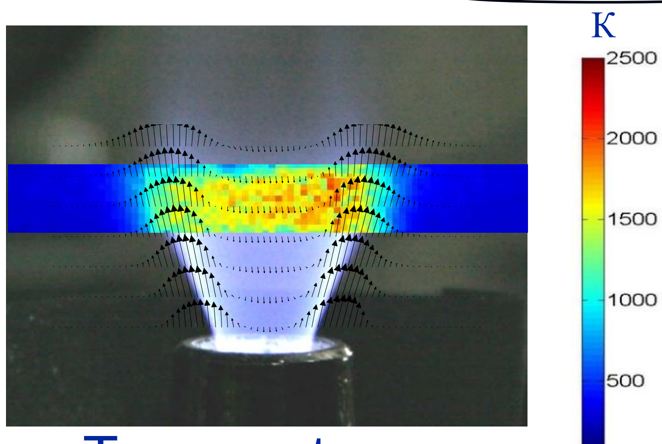
Comments: Particle Image Velocimetry (PIV) measures whole velocity fields by taking two images shortly after each other and calculating the distance individual particles travelled within this time. From the known time difference and the measured displacement the velocity is calculated.

Optical diagnostic of processes

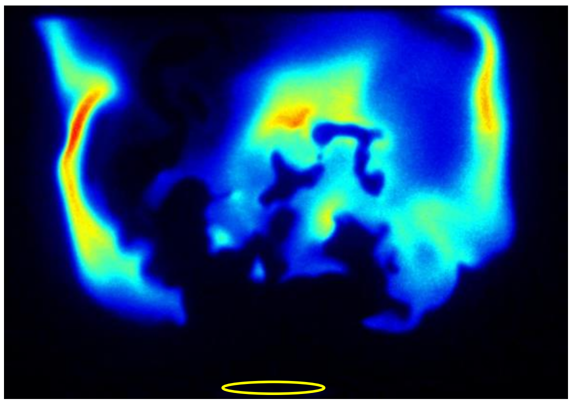
Velocity, temperature, concentration, radicals can be measured



Concentration



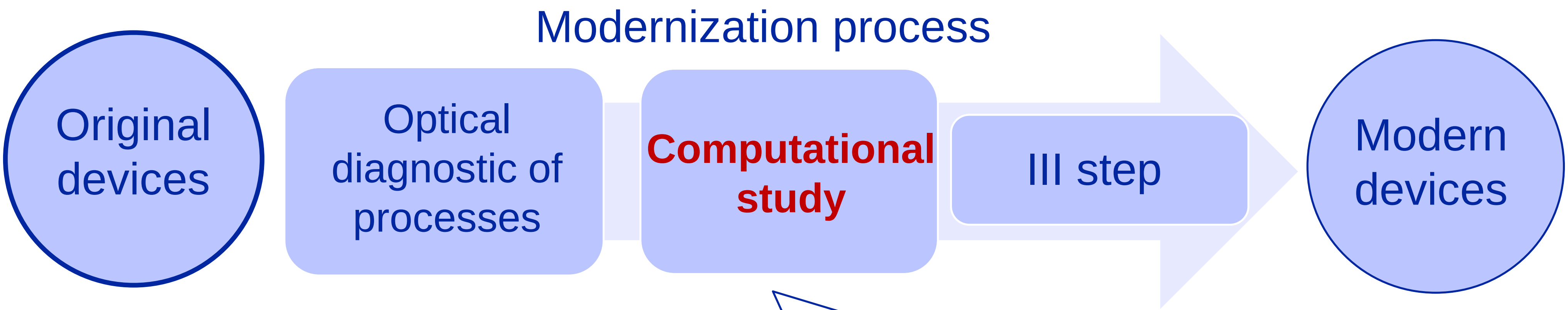
Temperature



Radicals CH*, OH*

Comments: Laser-induced fluorescence (LIF) is a spectroscopic method used for studying structure of molecules, detection of selective species and flow visualization and measurements. The species to be examined is excited with a laser. The wavelength is often selected to be the one at which the species has its largest cross section. The excited species will after some time, usually in the order of few nanoseconds to microseconds, de-excite and emit light at a wavelength longer than the excitation wavelength. This fluorescent light is typically recorded with a photomultiplier.

Procedure of development



Modeling allows us to **quick** and **cheap** analyze (compared to experiment) the flows in a wide range of control parameters: swirl, forcing, changing geometry etc.

Comments: In the next step we do computational study with T-FlowS computational code, taking experimental measurements as a basis for further modelling.

Computational study

TU Delft Delft University of Technology

T-FlowS is an open-source – open-access – in-house, flexible for modernize, unstructured finite-volume computational code, developed at the Delft University of Technology

Built-in capabilities:

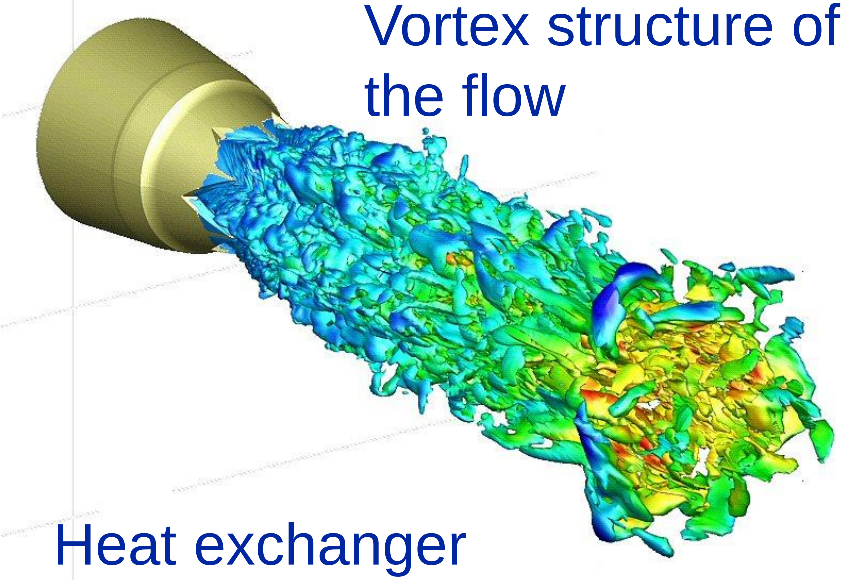
- Large Eddy Simulation (LES)
- Reynolds-averaged Navier-Stokes computations (RANS)
- Heat and mass transfer in complex configurations
- Combustion modelling in Low-Mach approximation

Comments: Large eddy simulation (LES) is a technique in which the smallest scales of the flow are removed through a filtering operation, and their effect modeled using subgrid scale models. This allows the largest and most important scales of the turbulence to be resolved, while greatly reducing the computational cost incurred by the smallest scales. This method requires greater computational resources than RANS methods, but is far cheaper than Direct Numerical Simulation (DNS).

Computational study

Study of flow structure and dynamics, ignition processes and pollutants formation

Vortex structure of the flow



Heat exchanger

Ignition process and flame surface propagation

Open burner

Comments: Detailed investigation of the physical processes in a wide range of control parameters in model devices: heat exchanger, open burner and combustion chamber, gas-turbine was carried out by using Large Eddy Simulation (LES) approach.

Procedure of development

Modernization process

Original devices → Optical diagnostic of processes → Computational study → **Data analysis** → Modern devices

Advanced numerical methods:

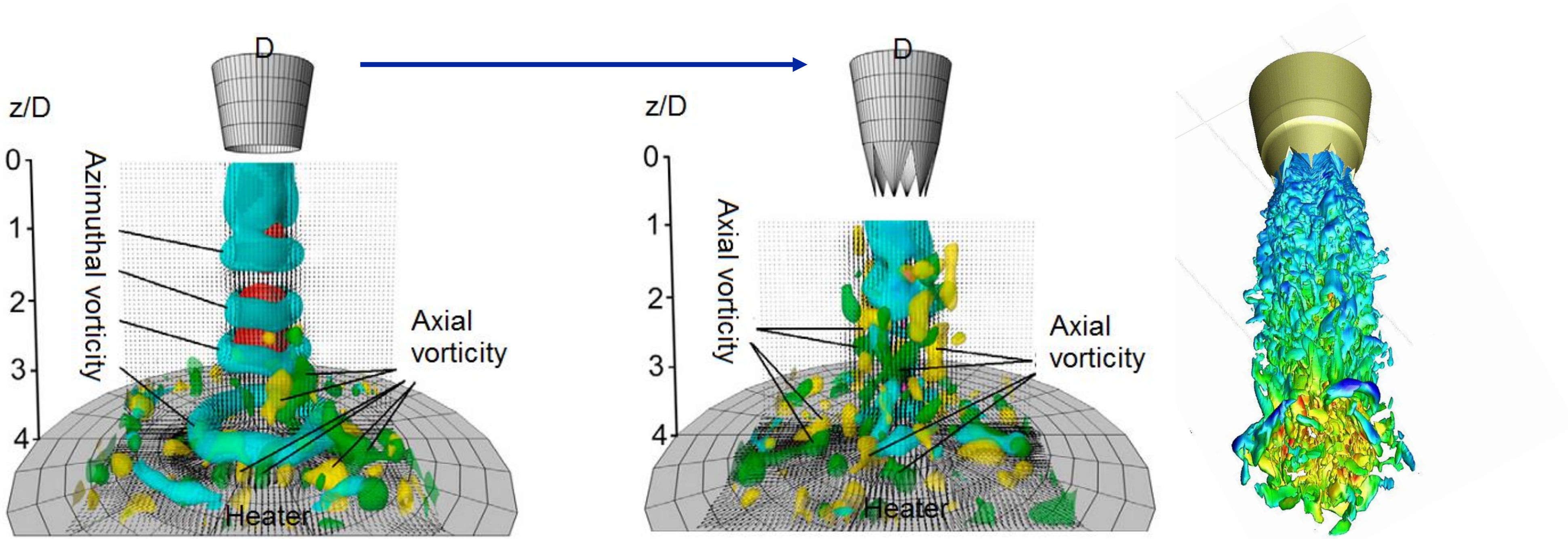
- Principal Components Analysis
- Dynamic Mode Decomposition
- Signal processing methods etc.

Comments: Principal component analysis (PCA) is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The Dynamic Mode Decomposition (DMD) is a mathematical method to extract the relevant modes from experimental data, without any recurrence to the governing equations.

Main results: Heat exchanger

Schlumberger

Intensification heat and mass transfer by modifying nozzle geometry



Experimental measurements

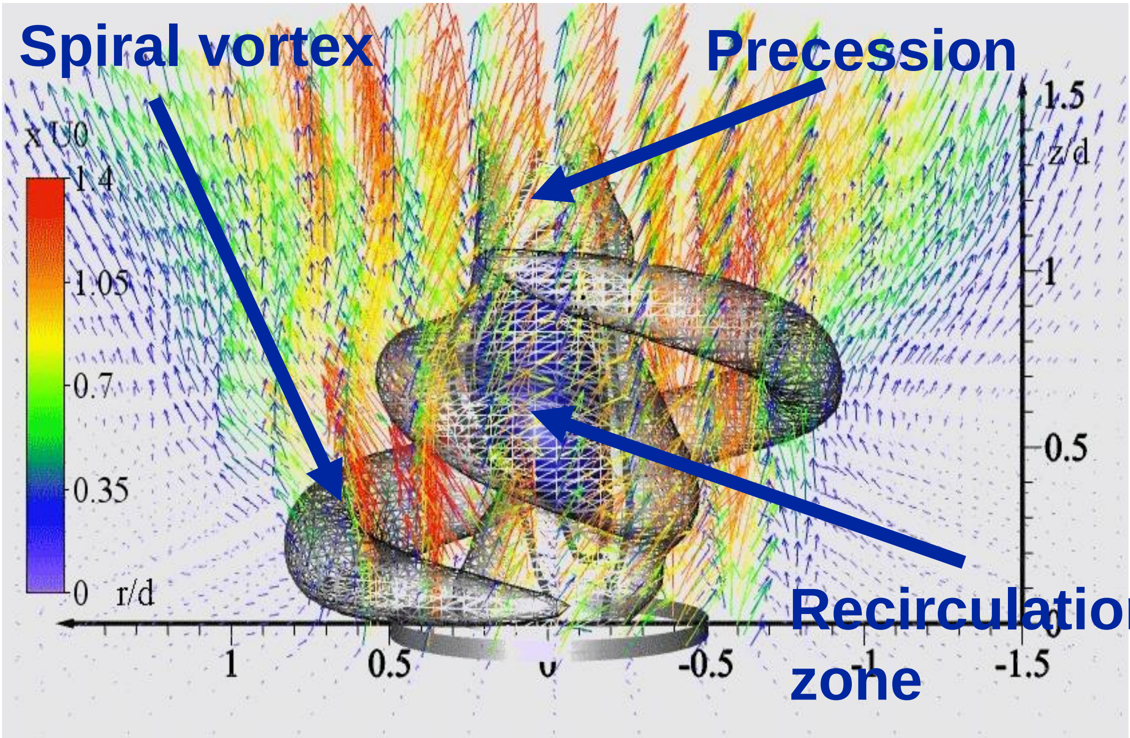
LES modelling

Comments: Experimental and computational study of flows in model heat exchanger was conducted by using Optical diagnostic measuring system and Large Eddy Simulation approach. It was found that modifying of nozzle geometry resulted in significantly increase of heat and mass transfer. Shevron nozzle in comparison with circular nozzle provided a more intensive mixing.

Main results: Open burner and Gas turbine

Effects from high swirl:

First useful regime



Fuel-rich high-swirl methane-air flame

Good

- ◆ Flame stabilization due to recirculation zone
- ◆ Enhanced mixing between fresh air and fuel
- ◆ High intensive combustion process

Bad

- ◆ Strong precession of vortex core
- ◆ Flashback effect
- ◆ High level of pollutants (NOx)

Comments: In the study of open burner and combustion chamber was found several effective, safe and environmentally friendly combustion regimes. In first useful regime we applied high swirl to the reacting flows in open burner and gas-turbine. In this work regime of devices, there were positive and negative effects. They are all listed in this slide.

Main results: Open burner and Gas turbine

Effects from low swirl:

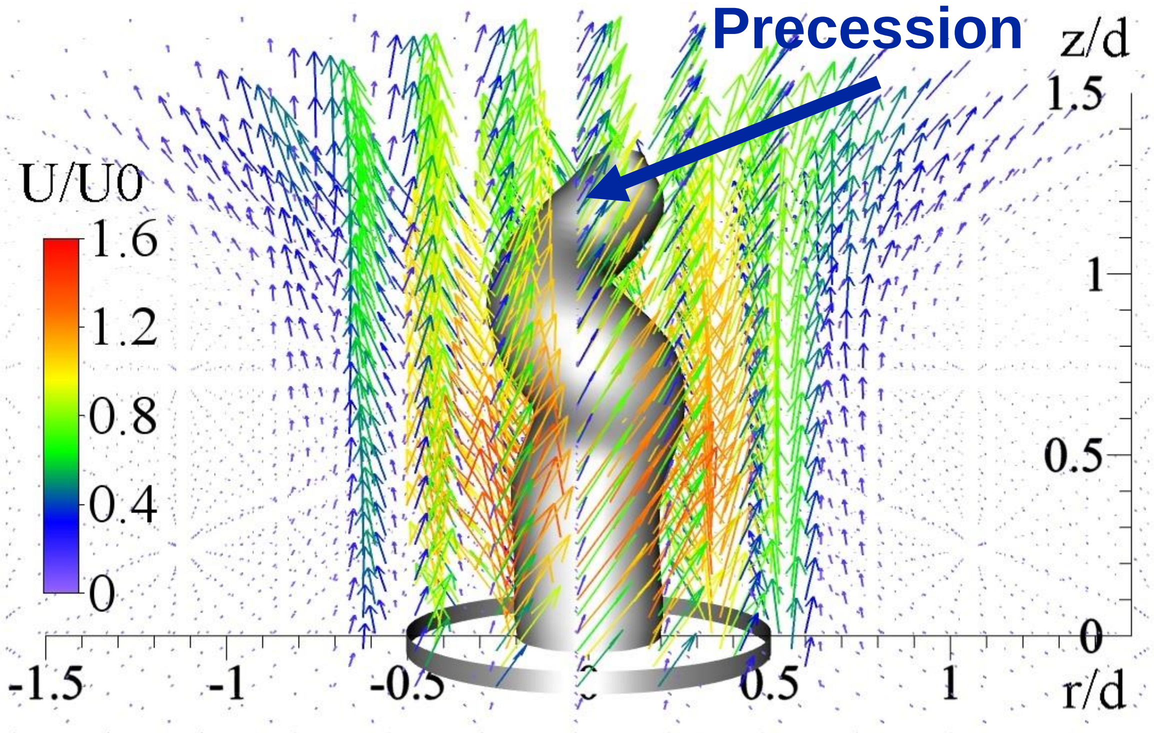
Good

- Swirl stabilization
- Low level of pollutants (NOx)
- No flashback effect

Bad

- Less mixing effect
- Less combustion intensity

Second useful regime



Lean low-swirl methane-air flame

Comments: We found that at low swirl rates (below a certain threshold) most of the negative effects that was observed in the first regime such as high level of NOx, flashback effect and strong precession can be significantly mitigated. But instead we got a very low level of mixing that affected the intensity of combustion.

Main results: Open burner and Gas turbine

Effects from high swirl and periodic forcing:

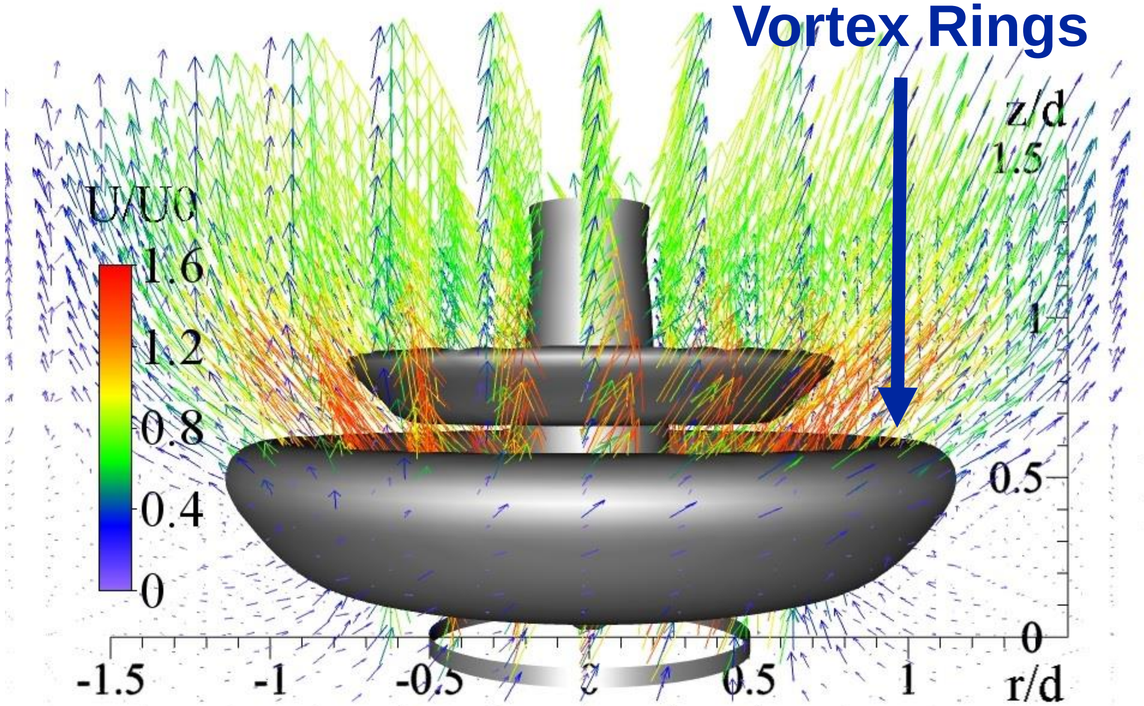
Third useful regime

Good

- Swirl stabilization
- No flashback effect
- High combustion intensity
- Intensive mixing

Bad

- Middle level of pollutants (NOx)



Forced high-swirl methane-air flame

Comments: Finally we found optimal combustion regime which combines high energy efficiency, safety and acceptable level of NOx emissions.

Conclusions and Future plans

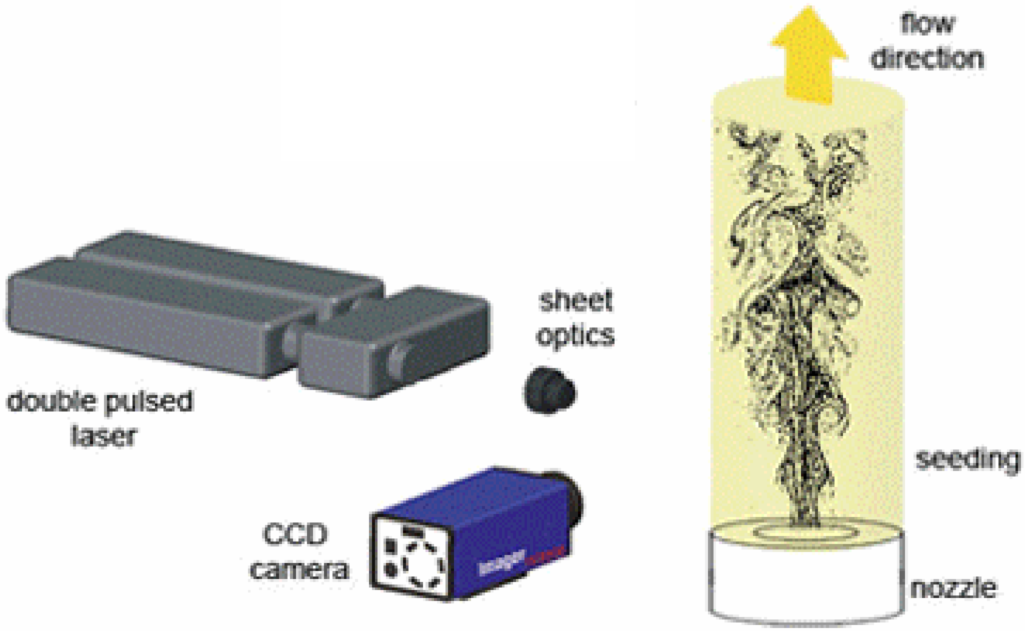
In the process of experimental and numerical study of 5 original energy devices: 2 heat exchangers, open burner and combustion chamber, gas turbine

- **Detailed information of physical processes occurring in these devices was obtained**
- **Ways to effective control of the flows in devices were presented**
- **In the study of open burner and combustion chamber was found several effective, safe and environmentally friendly combustion regimes**
- **It was found that modifying of nozzle geometry resulted in significantly increase of heat and mass transfer in heat exchangers**
- **Upgraded versions of devices were proposed**

- **Future Plans:**
  - **Development of effective modern combustion chamber on the basis of the study**
  - **Modernization of existing computational code T-FlowS for modelling turbulent reacting flows in large-scale energy devices**
  - **Publications in rating journals**

Particle Image Velocimetry

Schlumberger



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