FloEFD Application in Transportation

The Transportation Industries
Born in Aerospace

Aerospace Heritage

• FloEFD was born in Russian Aerospace Industry in early 80th
• Used by leading Russian and US aerospace companies

Separation in rocket nozzle: A very first validation of code made in collaboration with DLR (German Aerospace Centrum)

Grown in Automotive

Automotive Focus

• FloEFD has been growing high in Automotive
• Used by leading Automotive OEMs and Tier1-3s
FloEFD Sweet Spots and Why

FloEFD Capabilities
FloEFD Capabilities

**MAIN CALCULATIONS CAPABILITIES**
- Stationary or transient flows
- Heat transfer in gases and bodies (isotropic and anisotropic)
- Forced and natural convection
- Radiation heat transfer (surface radiation and absorption in bodies, grey and non-grey)
- Rotation (turbines and pumps)
- Electrical current through conductors
- Parametric Study

**INCOMPRESSIBLE**
- WATER (REAL LIQUID WITH POSSIBILITY OF CAVITATION)
- NEWTONIAN
- NON-NEWTONIAN LIQUIDS

**COMPRESSIBLE, M<3**
- STEAM (REAL GAS WITH POSSIBILITY OF CONDENSATION)
- WATER FILM HUMIDITY
- COMPRESSIBLE LIQUID

**HIGH MACH NUMBER, M<10**
- HYPERSONIC, M<30
- PARTICLE TRACKING
- JOULE HEATING
- COMBUSTION

**NEWTONIAN NON-NEWTONIAN LIQUIDS**
- Fans and heat sinks
- Porous media and Perforated plates
- Thermal and electrical contact resistance
- Thermolectric coolers (TEC)
- Heat Pipe, 2R-model, Electrical contact, PCB, Thermal Joint
- LED model
- Passive scalar and Comfort Parameters
- Other compact models

Real Gases Model

Redlich-Kwong state equation and three its modifications

15 predefined real fluids with modified Redlich-Kwong state equation:
- Water, Carbon dioxide (CO₂), Nitrogen (N₂), Propane (C₃H₈), Carbon monoxide (CO), Ammonia (NH₃), Oxygen (O₂), Methane (CH₄)
- Refrigerants: HFO-1234yf, R-134a, RC318, R123, R22, R410a, R245fa
**Flows With Phase Transitions**

*Steam as real gas with possibility of condensation*

Humidity (steam+ideal gas/gases)

$$\varphi = \frac{\rho_{\text{H}_2\text{O}}}{\rho_{\text{H}_2\text{O}_s}} \cdot 100\%$$, $\rho_{\text{H}_2\text{O}_s}$ – saturated vapor density at specified temperature and pressure

*Cavitation of water*

Water as real liquid with possibility of vaporization

*Cavitation of technical liquids (i.e. diesel fuel)*

“Isothermal” cavitation

\[ \rho = \rho(T, P) \]

**Non-Newtonian Liquids**

FloEFD is capable of computing laminar flows of inelastic non-Newtonian liquids optionally with Slip condition defined for each non-Newtonian liquids.

- Herschel-Bulkley model
- Power-law model
- Carreau model
- Cross-WLF model
- Second Order model

\[ \ln \mu(\dot{\gamma}, T) = C_1 + C_2 \ln \dot{\gamma} + C_3 \ln^2 \dot{\gamma} + C_4 T + C_5 T \ln \dot{\gamma} + C_6 T^2 \]

- Viscosity table model

This universal model defines the liquid’s viscosity by linear interpolation or polynomial approximation of the user-specified tabular dependencies of the viscosity on the shear rate at the various temperatures, i.e. the user creates the model from the experimental values provided.
Compressible Liquids

Compressible liquids whose density depends on pressure and temperature can be considered within the following approximations:

- obeying the logarithmic law
  \[ \rho = \rho_0 \left( 1 - C \ln \frac{B + P}{B + P_0} \right) \]

- obeying the power law
  \[ \rho = \rho_0 \left( \frac{P + B}{P_0 + B} \right)^{\frac{1}{n}} \]

- Fluid dynamic viscosity can be dependent on pressure and temperature:
  \[ \mu = \mu_0 e^{\alpha (P - P')} \]

Direct Current and Joule Heating

\[
\begin{align*}
\text{div } \vec{E} &= 0; \\
\vec{E} &= \nabla \varphi = \sigma \vec{J} \\
\Delta \varphi &= 0; \quad \vec{J} = \frac{1}{\sigma} \nabla \varphi
\end{align*}
\]

\[ W = \sigma (\vec{j}, \vec{J}) \] - specific Joule heating

Boundary conditions

Specified electrical contacts: electrical potential or electrical current.

Electric conductors properties

Specific electrical resistances of conductors are used from Engineering Data Base as one of solid material properties.
Combustible Mixtures

- FloEFD can account for the thermal effects of combustion of gas-phase mixtures.
- Equilibrium approach implies that the combustion starts immediately infinitely fast upon mixing (non-premixed condition).
- In practice there are many cases in which gas mixtures (fuel and oxidizer) are considered at room temperature and these mixtures do not burn at this premixed condition.
- In order to analyze such cases the equilibrium model was extended for premixed combustion mixtures and a “Limited Combustion Rate” option was added. This option extends the equilibrium model to the case of premixed combustion mixtures. In this case global chemical reaction is considered.

\[ M_o + M_f \xrightarrow{K(T)} M_p \]

Hypersonic

If a hypersonic flow of air is considered (at Mach numbers of 5 < M < 30, air density > 5\times10^{-7} \text{ kg/m}^3, i.e. the flight altitude of H < 100 \text{ km}), the effects of high-temperature air dissociation and ionization on the air properties are accounted in accordance with the equilibrium model.
Particles Movements

- Particle is considered as material point;
- Particle has spherical form;
- Particles movement does not influence on fluid flow;
- Particle is heated by the fluid with convection. Radiation is not taken into account for particles;
- There is no heat influence of particle on the fluid;
- Particle can mirror reflect from the wall, glue to the wall or has inelastic interaction.

\[
m_r \frac{d\vec{V}_r}{dt} = \frac{1}{8} \pi d_r^3 \rho (\vec{V} - \vec{V}_r) \mid \vec{V} - \vec{V}_r \mid C_d + \frac{1}{6} \pi d_r^3 (-\nabla P + (\rho_p - \rho) g)
\]

\[
m_r C_p \frac{dT_r}{dt} = \pi d_r^2 \rho c_w (T - T_f)
\]

Using this option particles trajectories, particles rate, erosion or sticking effects can be calculated. This option works for both solvers.

Water Film Model

- Capabilities
  - Condensation and Evaporation on surfaces
  - Icing/De-icing (frost effect)
  - Wettability property
  - Heat transfer along the film
  - Heat of phase transitions
  - Film motion on surfaces due to gravity and inertia forces
  - Transient simulation of humid air
  - Film thickness, phase, grow rate, temperature, mass, mass flux, heat flux at film boundary can be predicted

- Integral model
  - Thickness of the film is much less than mesh cell
  - There is no boundary of phase separation inside the film
  - The film is transparent for radiation
Radiation Modeling

- Thermal radiation, Environment radiation
- Solar radiation (with Ray Divergence),
- Diffusive, Specular and Gaussian reflection
- Geometric optics (focusing through lens, refraction)
- Absorption within semi-transparent bodies
- Wavelength dependency: daylight spectrum, wavelength dependency for emissivity and absorption coefficient
- Directional and Diffusive radiation source
- Gray and non-Gray model (band and ray-based spectral model)

Example to Demonstrate the Differences

DT Radiation
- No absorption in lens
- Good focus (v13)

DO Radiation (Lvl 7, 2nd Order)
- Absorption in lens
- No good focus

MC Radiation (1M rays)
- Absorption in lens
- Good focus
- Noisy
Interface to other Tools

- EDA Import
- Export to FEA and View Tools
  - ANSYS
  - NASTRAN based codes
  - MCS PATRAN
  - NX NASTRAN
  - Femap
  - Abaqus
  - Creo Simulate/ProMECHANICA
  - MpCCI
  - EnSight, ParaView

- Import from Optical Tools

- Interface with Optimization Tools
  - HyperStudy
  - modeFrontier
  - OptisLang, p7, IOSO

Key Advantages of FloEFD
Key Advantages of FloEFD

Handling complex geometry shapes
- FloEFD solver and mesher allows to handle of complex CAD models easily and effectively
- In most cases no need to simplify the geometry

CAD embedded
- Uses native parametric CAD models
- Ideal for a fast design cycle, complex geometry changing fast and often
- Saves time

Key Advantages of FloEFD

Incredible fast and easy meshing
- No man-hour spent on manual meshing which can be usually several days to weeks
- Special empirical-analytical models minimize requirement to mesh from the solver (one cell technology)

Easy-to-use
- Numerical knowledge requirements for engineers reduced
  - Robust convergence
  - Integral turbulence model
- Intuitive interface due to CAD embedding
- Can be used by non experienced CFD user

15 minutes not 2 - 2.5 weeks of meshing
The Main Outcome: Performance

Application: Jet Engine Core Compartment Cooling

<table>
<thead>
<tr>
<th>Task</th>
<th>Other CFD</th>
<th>FloEFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry preparation</td>
<td>30 h</td>
<td>16 h</td>
</tr>
<tr>
<td>Meshing, including setup</td>
<td>~40 h</td>
<td>1.1 h</td>
</tr>
<tr>
<td>Pre-processing</td>
<td>1 h</td>
<td>0.1 h</td>
</tr>
<tr>
<td>Pre-processing total:</td>
<td>~70 h</td>
<td>~ 17 h</td>
</tr>
<tr>
<td>Solving</td>
<td>30 h (16 CPU)</td>
<td>30 h (8 CPU)</td>
</tr>
<tr>
<td>Results processing</td>
<td>1 h</td>
<td>1 h</td>
</tr>
<tr>
<td>Total cycle time</td>
<td>~11 days</td>
<td>5 days</td>
</tr>
<tr>
<td>Total user input time</td>
<td>~ 80 h</td>
<td>~ 18 h</td>
</tr>
<tr>
<td>Results accuracy</td>
<td>&lt; 3.8%</td>
<td>&lt; 4%</td>
</tr>
</tbody>
</table>

User Applications
Valves and regulators
Air Management Systems
Aerodynamics
Engine Simulation
Electronics Cooling
Lighting
FloEFD Sweet Spots
Aerodynamic Heating

Forces Prediction

Hypersonic Flow

Ty-214 Airplane (M=0.6)

<table>
<thead>
<tr>
<th>M</th>
<th>$C_y^{exp}$</th>
<th>$C_y^{FloEFD}$</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.1154</td>
<td>0.1134</td>
<td>1.73%</td>
</tr>
<tr>
<td>0.83</td>
<td>0.1458</td>
<td>0.1399</td>
<td>4.36%</td>
</tr>
</tbody>
</table>

* Calculation results of JSC «Tupolev».
Hypersonic Flow (M = 5.8 .. 6.1)

Angle of attack

Aerodynamic Heating

Time = 36.0 s

Temperature (Solid) [°C]

Temperature (Gas) [K]

α = 0°
Valves Design
Fuel Tank Design
Electronics Cooling
Heat Exchanger
Puralator save 2 months in Design of Cyclonic Particle Separator for Jet Engines

Puralator-Facet is a US based leading developer of filter related components for various industries.  
**Challenge:** Redesign a cyclonic inertial separator for a Pratt & Whitney military jet engine.  
**Benefits:**  
- CFD analysis allowed for testing of 27 design variants without a prototype  
- **Project completed in 6 months, saving 2 months, and resulted in a patent-pending new Separator design**  
- Traditional CFD tool had failed to do the study  
- $1,000's saved.

"We saved 2 full months of development work and delivered the project to the customer on time. As far as helping us modify the relationship between pressure drop and filtration efficiency, we used FloEFD to break some of the established paradigms of cyclonic inertial separator design."

David Rachels, Director of Engineering, Purolator-Facet.

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Shaw Aero* Reduce Valve Prototype Development Time from 3 Months to 1Day

Shaw Aero Devices designs, develops and manufactures a wide range of products in the areas of fuel, oil and water/waste systems and components.  
**Challenge:** Develop a new solenoid valve for an unmanned aerial vehicle cost effectively  
**Benefits:**  
- Met their customer’s precise pressure drop requirements  
- **Reduced development time from 3 months to 1 day**  
- Reduced engineering costs by replacing physical prototypes

"EFD simulation dramatically reduced the time needed to meet our customer’s demanding specifications. "Without CFD, we would have had to go through a minimum of three prototypes, more likely several more. With CFD we moved from the beginning of the project to the development of an acceptable software prototype in only one day."

Robert Preble, Project Engineer, Shaw Aero.

*Shaw is now part of Parker Aerospace*
Bell Helicopter manufactures helicopters designed for a broad range of commercial and military applications. The latter class of aircraft includes defensive features designed to protect the helicopter and its occupants in the most adverse situations.

**Challenge:** Review and refine a system that injects nitrogen gas into the helicopter’s fuel tank to displace oxygen as the fuel is consumed making the tank less likely to ignite if it is hit by an incendiary projectile.

**Benefits:**
- Analysis of the fuel tank’s internal flow characteristics found potential venting problems
- CFD by designers **saves on expensive and time consuming physical testing**
- Using these results, the problem was redesigned and corrected before the prototyping phase
Engine Underhood Fire Simulation

Initial fire (w/o refrigerant)     Fire after adding refrigerant
Lighting Application Sweetspots

**Headlight Simulation**
- Determine suitable material for manufacturing according to temperature limits
- Simulate solar load onto lenses with focal point position
- Analyse whole headlight thermal management
- Improve evaporation speed of film condensation

**Component simulation**
- Analyse LEDs on PCB and heat sink performance
- Optimize PCB and heat sink design and material
- Determine hot spot of lens modules for temperature and location of the hot spot
**Lighting**

**Cabin & HVAC**

**IC Engine Design**

**Radiator/Heat Exchanger Design**

**HEV/EV Powertrain**

**Infotainment**

FloEFD Sweet Spots

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**Infotainment / Instrument Cluster / HUD’s Application Sweetspots**

**Dashboard**

**Mechanical & Electrical Design:**
- Integration of electronics into dashboard

**Ducting design and airflow management:**
- Vent design, sizing and location
- Flow of air to electronics systems
- Temperature of cooling air

**Instrumentation & Multimedia Systems**

**Thermal management:**
- Concept design analysis through to detailed design
- Predict temperatures of components and LEDs used for backlighting
- Ensure PCB is below temperature limit
- Design space exploration using DoE techniques
- Design optimization
Cabin/HVAC Application Sweetspots

Cabin Modelling
- Analyze climate control functions and passenger comfort:
  - Important to meet health & safety requirements
  - Windscreen de-icing and de-fogging
  - Passenger comfort under various (harsh) conditions

HVAC Ducts and Fans
- Analyze and improve the flow field in vehicle heater systems:
  - Air flow pattern
  - Flow distribution
  - Pressure distribution
  - Optimisation of fan blade and volute geometry
  - Calculate fan performance

FloEFD enables CFD to be introduced into design departments.
**FloEFD Sweet Spots**

**E-Drive Application Sweetspots**

**Electric Motor/Generator**
- Analyse thermal performance
- Considering winding losses
- Air and coolant flow simulation
- Rotation of rotor
- Optimize housing and water jacket design
- Optimize winding and gap design

**Battery**
- Analyse flow distribution and pressure loss
- Air and coolant flow simulation
- Optimize cooling pack design

Electronic Module Design Application Sweetspots

Electronic Control Units (ECU)
- Electronics cooling...
- Predict chip temperatures
- PCB thermal management
- Enclosure design with heat sinking
- Heat transfer into car frame
- Influence of hot engine environment
- Radiative heat transfer
- Import of EDA data
- TIM thermal conductivity

Image Source: Munic.Box

E-Drive System

E-Battery

E-Motor

E-Drive

E-Clutch

E-Transmission

E-Converter

E-Inverter

E-Drive System

Electronics Module

IGBT

Lithium-Ion Battery

Power Electronics

Image Source: Munic.Box

FloEFD Sweet Spots

Infotainment

Cabin & HVAC

Lighting

IC Engine Design

Radiator/Heat Exchanger Design

HEV/EV Powertrain
Internal Combustion Engine Design Application Sweetspots

Engine Cooling
- Analyze heat transfer within a cylinder head:
  - Flow of coolant
  - Uniformity of cooling
  - Temperature gradients
  - Head warp age

Intake Systems
- Turbochargers:
  - Optimisation of turbocharger blade geometry and volute design
- In-Cylinder Flow:
  - Study the 3D flow field
  - Visualize position and size of vortices
  - Study flow field at various nozzle positions
  - Analyze influence of nozzle shape and position

Analyse and improve flow performance and thermal behavior:
- Flow rate distribution
- Pressure drop
- Transient simulations
- Temperature distribution
- Test manufacturing options
- Test packaging options

Exhaust Pipes and Manifolds

FloEFD Sweet Spots
Radiator / Heat Exchanger Design Sweetspot

**HX Component**

**Mechanical & Electrical Design:**
- Integration of electronics into dashboard

**Liquid Intercoolers**
- Temperature management

**Ducting design and airflow management:**
- Vent design, sizing and location
- Flow of air to electronics systems
- Temperature of cooling air

**Challenge:**
- EGR: Mixing of exhaust gas with inlet air
- Comparison of EGR mass fraction for two designs
- Design of an air duct from turbo compressor
- Study water velocity distribution in cylinder head jacket

**Benefit:**
- Virtual testing of mixing efficiency and selection of the best variant based on virtual prototypes
- Better understanding of flow field for performance improvements
- Expensive field experiments avoided

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**Intake Air Duct and Cooling Jacket Design**

**Challenge:**
- EGR: Mixing of exhaust gas with inlet air
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- Design of an air duct from turbo compressor
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Throttle Body Valve for Engine Aspiration

• Challenge:
  • New throttle valve for engine aspiration

• Benefit:
  • Designers required only a half day of training to become competent and the results were as good as those from traditional CFD codes used by specialists.
  • Design engineers reduce thermal loads and optimize airflow patterns during design stage.
  • CAD integration allowed quick design studies.

“At first we purchased 1 license of FloEFD, but soon afterwards we realized 1 license was not enough. We decided to buy 2 more seats of EFD but the designers still fight over who will use the licenses. Due to the ease-of-use, designers can understand the fundamental operation after only 1 or 2 hours of training. And the results are as good as with traditional high-end CFD products.”

Masayuki Sato, Hitachi Seisakusho, Japan

Clutch Fluids

• Challenge:
  • Analyse flow of transmission fluid into geared components within an automotive clutch housing modelled in FloEFD
Heaters for Cars and Trucks

Challenge:
- Analyse and improve the flow field in vehicle heater systems:
  - Air flow pattern
  - Velocity and pressure distribution

Benefit:
- Company wanted to reduce the costs for CFD significantly
- Introduction of CFD simulations into their design department.

Intake Manifolds

• Challenge:
  - Ensure required flow rates
  - Match various implementation conditions
  - Flow rate optimization vs. manufacturability
  - EGR modeling

• Benefit:
  - Understanding of influence of shape changes
  - Design variations for structural analysis
  - Simulation of EGR mixing processes
**Fuel Injector - Cavitation**

**Challenge:**
- Simulate flow through an automotive fuel injector showing the development of cavitation as the downstream pressure is reduced.

**Hydrocarbon Trap**

Miniature Precision Components is a leader in the design and manufacture of injection molded emission control components. The company saw the need for a cost competitive hydrocarbon trap for a partial zero emission vehicle (PZEV) which is 90% cleaner than the average new car.

**Challenges:**
- Design a Trap that captures nearly all hydrocarbons while avoiding air backpressure increase entering the engine

**Benefit:**
- Evaluated 12 different design alternatives to minimize backpressure and achieve required absorption specification
- Final design from CFD predictions was tested with a prototype and good agreement with measurement

“The ability to visualize the flow helped me understand where the restrictions were in each design and provided insight into how to reduce the backpressure.”

M. Van de Bogert, Product Design Manager, MPC Inc.
FloEFD Helps Save 4 Months in Design of an Automotive Valve

Ventrex Automotive is a successful supplier of components to the German automotive industry

Challenge:
- Develop a new environmentally friendly valve in support of CO2 based automotive air conditioning systems at 7-10 times higher pressures

Benefits:
- Reduced the number of prototypes by 50
- Reduced pressure drops so that flow rates improved by 15%
- Saved four months of design time
- Predicted CFD performance seen in practice
- Introduced new product to market faster

“FloEFDV5 because it simplifies the process of performing fluid flow analysis to the point where it can be accomplished by any engineer. By using CFD software that is embedded into our CAD software we could evaluate the performance of each new design iteration almost as fast as we could conceive it.”

Daniel Gaisbacher, Project Manager, VENTREX Automotive GmbH

Heat Exchanger with Real Gas

Pre-defined fluids:
- R-1234yf (HFO-1234yf)
- R-123
- R-124a
- R-22
- R-245fa
- R-410a
- RC318
Brake Disk Cooling

Challenge: Analysis of thermal behavior of brakes and cooling performance

Flow velocity -100 km/h
Brake disk: f=10 rps; t=400 C

Electric Engine Design

• Challenge:
  • Allow for sufficient engine cooling through channels in walls
  • Narrow channels resulted in large pressure loss so channels needed to be widened
  • Thicker walls could result in loss of seating

• Benefit:
  • Remove cooling channels
  • Loss of seat was averted
Conclusion

Summary

• FloEFD capabilities are wide

• Customer applications are wide

• FloEFD has unique technology which brings significant performance gain to the user
ExoMars (Exobiology on Mars)

ExoMars (Exobiology on Mars) is an astrobiology project to investigate the past habitability environment of Mars and to demonstrate new technologies paving the way for a future Mars sample return mission in the 2020s.

ExoMars is a joint mission of European Space Agency (ESA) and Russian Federal Space Agency (Roscosmos).

Thank You