Abstract

Water is an efficient and environmental friendly means to mitigate and extinguish fires. However, it is not easy to judge the efficiency of water based mitigation and extinction systems due to complexity of the physics and geometry. Therefore advanced computation systems, like Kameleon FireEx (KFX) must be utilized for a prediction of the interaction between the fire, its environments and the water droplets.

Generally water droplets do not extinguish fires in the gas phase. When water droplets hit a fuel emitting surface like a pool of hydrocarbons, or a burning surface material, then the fire may become extinguished. Water droplets and water vapour do, however, have a mitigating effect on both kind of fires due to the screening of radiative heat transfer.

Water droplets can also extinguish fires in the gas phase when they become small enough, i.e. in the size range of 100 μm because then they become small enough to interact with the reacting structures in the flame, which are in the same size range. Water mist systems are extinguishing systems of this kind.

KFX includes all necessary physics related to water droplets in fires like droplet movement, evaporation, radiation screening including spectral effects, extinction, water droplets interaction with fire engulfed objects etc.

Physics of fires

Due to buoyancy forces created by the big temperature differences, the flow pattern in a fire is turbulent. The turbulence is characterized vortices in a wide spectrum of sizes, ranging from the dimensions of the linear scale of the fire down to, and even smaller than, the so-called Kolmogorov scales. This means from meters down to fractions of a millimeter. The mechanical energy of turbulence, $k$, is created through the interaction between the mean flow and the turbulence. While the production of $k$ takes place in the larger scales of turbulence its dissipation takes place in the smallest vortices in the fine structures of turbulence, where the molecular mixing takes place. This is consequently the domain for the chemical reactions.

The above is inherent in turbulent combustion in general whether it is in fires, gas turbine combustors or piston engines.

Figure 1 shows a cut through a laminar diffusion flame taken by the Laser Induced Fluorescence technique (LIF) depicting a reacting specie. Figure 2 is a similar cut through a premixed turbulent flame.
Figure 1: Serh15t.pcx by Pia Magnussen

Figure 2: Ajflfr8t.pcx by Pia Magnussen

Both pictures show that the reaction space is localized to thin structures either sheets or vortices. This is of major importance for the understanding and modelling of chemical reactions in turbulent flow.

**Water droplets in fires**

Water droplets sprayed into a fire interact with the fluids, the gases, in the flame through the drag forces. These forces will retard the droplets movement at the same time as it accelerates the gaseous fluid, or vice versa.

The movement of the droplets are consequently influenced by the mean flow of the gas as well as by turbulence and gravitational forces. Due to the high temperatures and strong radiation in the flame, water will evaporate from the droplets which eventually will disappear or pass through the flame and hit surrounding surfaces or internal objects.

Under certain conditions, generally in the vicinity of the spray nozzles, the forces acting on the droplets may become so strong that the surface tension in a droplet is not able to keep the droplet contained and consequently breaks up into smaller droplets. This effect must of course be treated properly in computational simulation of water droplets movements in flames in order to secure that the computation is not treating non-physical droplets.

Water droplets, when sprayed into a fire or applied like water curtains outside the fire, will have a mitigating effect on the heat transfer from the fire either through the temperature reducing effect due to water evaporation, or through the screening effect on radiation, due to heat absorption in the droplets.

The absorption of radiation in a droplet is dependent on the droplet diameter and the wavelength of the incident radiation. The absorption of light is very small, as we all know, while radiation in the infrared range, from approximately two microns and upwards, nearly gets completely absorbed even in very small droplets. This means that when considering the radiation screening effect of water droplets one must know about the frequency distribution of the incoming radiation.

The rates of the chemical reactions are strongly temperature dependent. Under normal flame conditions the flame temperatures are so high that the thermal reactions are fully able to produce sufficient heat to balance the heat absorption and the heat loss from the reaction space. As explained previously the reaction space is contained in the fine structures. Thus in order to extinguish reactions in the gas phase, these structures must be cooled to temperatures in the vicinity of 1200-1300 K. This can only be achieved by water droplets that are sufficiency small such that the evaporation will be sufficiency large in the passage of the thin reaction structures. Consequently the droplets must be in the size range of approximately 100 micros or smaller. Droplets in this size range are in the so-called mist area.

Larger droplets may also extinguish fires like pool fires or in solid material by the effect on evaporation or gasification.
Kameleon FireEx (KFX)

KFX is a fully three-dimensional transient CFD-code developed by ComputIT on the basis of previous developments in the environment of thermodynamics at Norwegian University of Science and Technology and SINTEF.

It is based on solution of the Navier Stoles equations with sub-models as follows:

- Governing equations:
  Time averaged Navier-Stokes-equations (3D)
- Turbulence model:
  $k-\varepsilon$-model
- Combustion model:
  Eddy-Dissipation-Concept, EDC
- Soot model:
  "Magnussen" soot model
- Radiation model:
  Discrete Transfer Model (Lockwood and Shah)
- Spray model:
  Lagrangian description of discrete droplets

The Eddy Dissipation Concept of Magnussen (EDC)

The basis of the EDC concept is a method for treating the interaction between the reacting fine structures and the surrounding fluid. Figure 3 illustrates the basic principle, where the fine structures are treated like homogeneous reactors.

![Figure 3: Model view of the EDC](image)

The characteristics for the mass fraction contained in the fine structures, the fraction of the fine structures reacting, as well as the exchange rate between the fine structures and their surroundings are linked to the turbulent kinetic energy, $k$, and its rate of dissipation, $\varepsilon$ (Figure 4).
This concept allows for detailed treatment of complex chemistry in turbulent flow including extinction as well as for more simplified treatment where the thermal reactions are treated as infinitely fast reacting to equilibrium.

The treatment of water droplets in KFX

The movements of the water droplets are treated in a Lagrangian way while the gas phase is treated in the Eulerian way, that means in relation to a fixed computational grid.

The break up of droplets are treated by a Weber number criterion, in such a way that droplets are subsequently broken up until the Weber related criterion is satisfied.

The radiation absorption in droplets are treated as follows by a method developed at ComputIT in relation to the discrete transfer method of Lockwood and Shah.

The energy absorbed can be expressed,
\[
\frac{I_a}{I_o} = 1 - e^{-\sum_{N} \left( \kappa_a(r_d, T) \cdot r_d^2 \cdot N_{r_d} \right) L}
\]  

(1)

where

\( I_a \) = absorbed energy along the path length, \( L \)

\( I_o \) = incident radiation

\( \kappa_a(r_d, T) \) = absorption coefficient for the droplets with radius, \( r_d \), averaged over all wavelengths

\( r_d \) = radius of droplets

\( N_{r_d} \) = number of particles with specific radius, \( r_d \), per unit volume

The absorption coefficient is wavelength dependent

\[
\kappa_a(\lambda, r_d) = 1 + \frac{2\left(e^{-\alpha n k} + (e^{-\alpha n k} - 1)/4\alpha n k\right)}{4\alpha n k}
\]

(2)

where \( \alpha = \frac{2\pi r_d}{\lambda} \)

\( n \) and \( k \) are given by the complex refractive index, \( n + ik \), where \( n \) and \( k \) are functions of the wavelength, \( \lambda \), (cfr Fig. 5)

![Figure 5: Optical constants for liquid water](image)

The absorption constant \( \kappa_a(r_d, T) \) as a function of the gray gas temperature, \( T \), can now be worked out by integration over the Plank distribution function. The result is depicted in Figure 6.

Figure 6: Parametric variation of the absorption factor of water in respect to the droplet diameter

Water sprays from nozzles are treated by a certain number of parcels of droplets with prescribed droplet diameters to be released from the nozzle. A number of nozzles with different characteristics arranged in different ways can be handled by KFX. The following figures demonstrate some characteristics.

Figure 7: Multi spray water curtain

Figure 8: Multiple fan shape spray water curtain
Figure 9: Multiple bore mist nozzle

Figure 10: “Fat” Spray monitor

Figure 11: Numerical calculation of water curtain radiation shielding experiment

Figure 10 demonstrates the radiation shielding effect of a water curtain as computed by KFX.

Figures 11-16 show some results from a comparison between experimental data and computations from a rather complex fire test scenario.

Figure 12: Side view of test rig

Figure 13: Top view of test rig
Figure 14:

Figure 15: Ray trace picture of early stage of water release

Figure 16: High velocity nozzles. Heat load at 3 meters broad-wise at the same level as the jet nozzle. Water is released at 360 seconds.

Figure 17: Medium velocity nozzles. Heat load at 3 meters broad-wise at the same level as the jet nozzle. Water is released at 360 seconds.

KFX in practical application

KFX includes advanced computation operational facilities, including CAD inputs and outputs which allows for a flexible adaptation of KFX to the specific problem scenario, in complex release conditions.

The presentation shows a number of computed fire and fire mitigation scenarios from ComputIT’s industrial activity. Videos show the time evolution of the fires.
**Conclusion**

KFX in its present version is capable of simulating complex fire and fire mitigation scenarios with high confidence in the computational results.

Extensive developments and validation activities are continuously going on through the financial support of Statoil, Hydro, Total, ENI group and ConocoPhillips.

KFX is licensed to a number of users world wide.