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CFD MODELING OF LARGE CROWN FOREST FIRE BEHAVIOR

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Overview

- Introduction: Computational Fluid Dynamics (CFD) and forest fire modeling
- Customizing CFD for wildfire behavior analysis
- PHOENICS CFD software and ACFDA capabilities
- WILDFIRE case study: modeling large crown wildfires (multiple plumes)
- WILDFIRE case study: model input/output, model features, equations, geometry, results
- Future studies: model validation; effects of atmospheric conditions, terrain, forest geometry, its composition and chemistry, etc.)
- Summary: wider use of CFD tools for forest fire modeling (fire researchers and fire managers/engineers), collaboration

Introduction: CFD and forest fire modeling

- **Forest Fire Behavior Research Challenges:**
  - Multi-physics: multiphase flow, turbulence, phase change, homogeneous and heterogeneous combustion, radiation
  - Multi-scale: small solid particles and large domain sizes
  - Expensive and dangerous experimentation
  - Need for accurate model predictions
- **CFD capabilities:**
  - Commercial general-purpose CFD codes (PHOENICS, FLUENT, CFX, etc.) - framework for modeling forest fires
  - Customizing CFD codes for forest fires
  - Validating the customized models
  - CFD models as scientific basis for fire behavior predictions and decision making
  - Safe and cost-effective prediction tool (effect of input parameters and virtual reality interface)

Customizing CFD for wildfire behavior analysis

- General-purpose CFD software packages are equipped with all the modeling capabilities needed for forest fire behavior prediction but some customization is needed
- **General CFD governing equations include:**
  - conservation equations for mass, momentum and energy for each phase of multi-phase medium (forest fire),
  - constitutive equations (linkage between phases)
  - turbulence model equations,
  - chemical kinetics equations (homogeneous and heterogeneous reactions)
  - equations for radiation heat transfer
- **Customizing CFD for forest fire modeling:**
  - Selecting a proper option from list of models available
  - Accounting for special input (atmospheric stratification, terrain, forest composition, details of chemical kinetics, fire type, etc.)
  - Validating customized models using experimental data
  - Applying models as a cost-effective and accurate predictive tool

PHOENICS CFD software and ACFDA capabilities

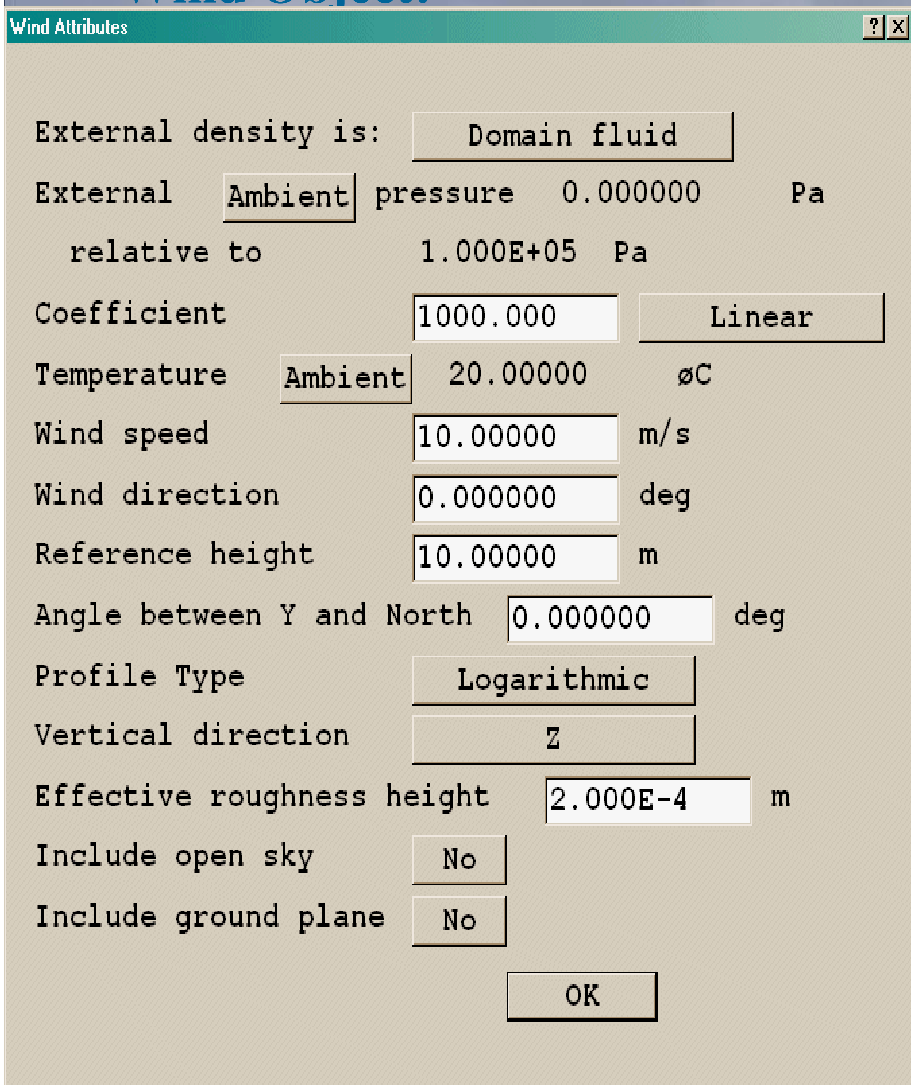
- **PHOENICS software capabilities (www.cham.co.uk and www.acfda.org):**
  - 30 years of research, development and validation
  - More than 4 thousand users around the world
  - Advanced CFD models (turbulence, two-phase, combustion, radiation)
  - Virtual Reality interface (easy input and output)
  - Easy to customize for specific applications (INFORM, etc.)
  - Widely used for modeling combustion and atmospheric flows
  - Is being customized for forest fire modeling
- **ACFDA research team (www.acfda.org/team.shtml):** four PhDs each having 25+ years of experience in CFD and combustion (both academic and industrial) including 1 PhD with 25 years of experience in CFD modeling of forest fires
- **ACFDA products and services**:
  - CFD software sales, consulting, training and user support
  - Advanced customized CFD modules for forest fire modeling

ACFDA capabilities: some customized models

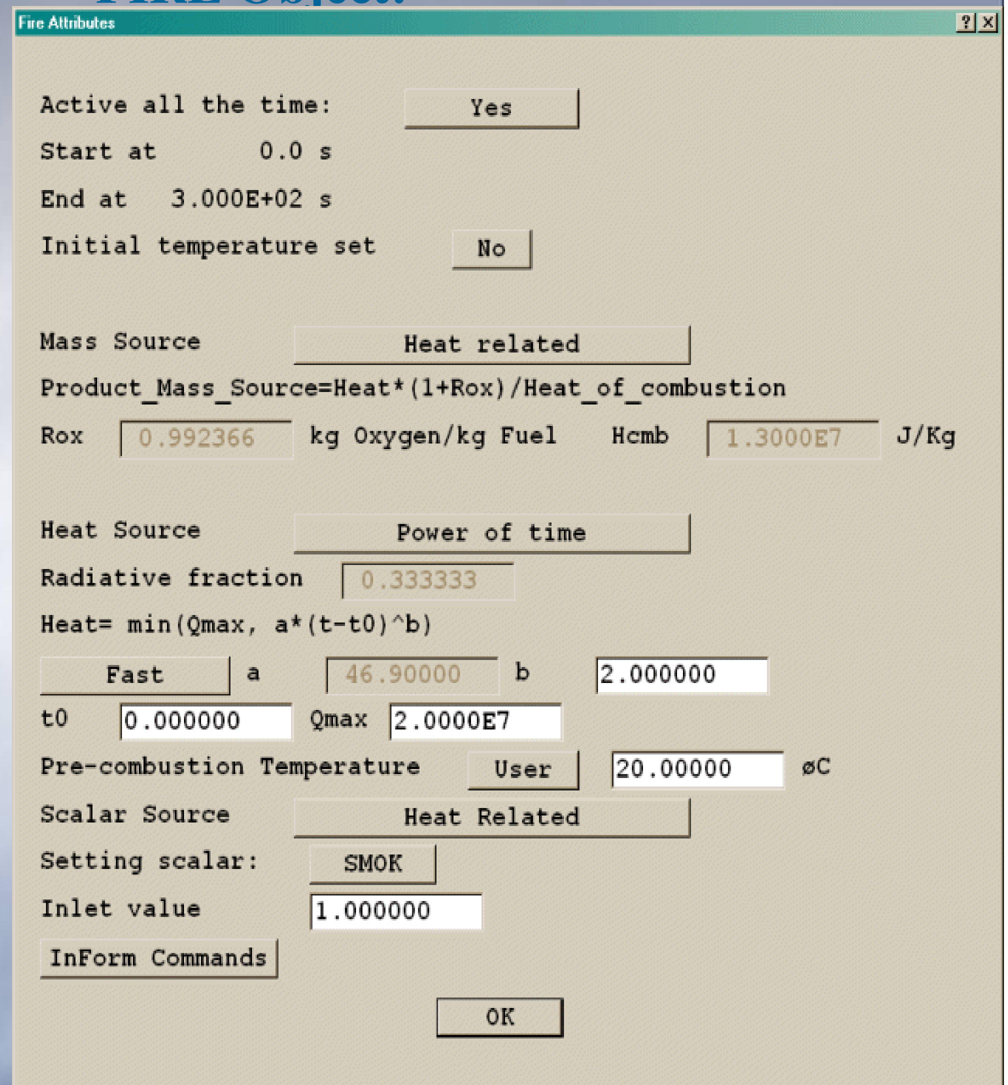
- **Recent advanced customized CFD models (http://www.acfda.org/docs/gtc_presentation_agranat.pdf):**
  - **GLFLOW module,** for analyses of complex gas-liquid flows and heat/mass transfer in complicated geometries (no limitations on flow regime):
    http://www.acfda.org/docs/GLFLOW_Capabilities.pdf
  - **GRAD CFD module**, for advanced CFD modeling of Gas Release and Dispersion (safety and environmental):
    http://www.acfda.org/docs/GRAD_for_CHAM_2009.pdf
  - **COALGAS module,** for modeling of coal/wood/biomass gasification and combustion:
    http://www.cham.co.uk/phoenics/d_polis/d_applic/d_comb/coalgas/coalgas.htm
  - **WILDFIRE CFD module,** for modeling wildfire behavior: work in progress (this paper)

PHOENICS software: available WIND and FIRE objects

- **Wind Object:**



- **FIRE Object:**



WILDFIRE case study: modeling large crown wildfires (multiple plumes)

- Large crown wildfires are observed at high head fire intensities (I>2500 kW/m): [1] Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. Vol. 7
- They are dangerous and difficult to study experimentally (International Crown Fire Modeling Experiment or ICFME): [2] Stocks, B.J. et al. 2004. Crown fire behaviour in a northern jack pine- black spruce forest
- Powerful thermal plumes are formed by crown wildfires: [3] Grishin A.M. 1997. Mathematical modeling of forest fires and new methods of fighting them. Publishing House of Tomsk University, Tomsk, Russia, Edited by F. Albini
- Multiple crown fires could be observed due to spotting: [4] Grishin A.M. 1981. Mathematical models of forest fires. Tomsk University (in Russian)
- Head fire intensity and wind speed affect the wildfire behaviour: [5] Nelson, R.M., Jr. 1993. Byram's derivation of the energy criterion for forest and wildland fires. Int. J. Wildland Fire Vol. 3 (3)
- CFD models could be cost-effective tools to predict interaction between multiple wildfires and atmosphere, fire spread, etc.

WILDFIRE case study: model input and output

- Model input:
  - Geometry of domain of interest (forest, fires, terrain and atmospheric boundary layer)
  - Forest fuel characteristics (composition, etc.)
  - Fire type (e.g. crown fire), its geometry and fire intensity
  - Available empirical correlations (semi-empirical models)
  - Atmospheric conditions (stratification, wind speed, humidity, etc.)
- Model output:
  - 3D distributions of pressure, velocity, temperature and species concentrations
  - Detailed picture of hydrodynamic and thermal interaction between multiple fires and wind
  - Radiation heat fluxes (safety and fire spread)
  - Smoke distribution
  - Any special (user-defined) output

WILDFIRE case study: model features

- Forest as a porous medium
- Crown wildfire as a fixed heat- and mass source defined based on head fire intensity (empirical data)
- Multiple wildfires are considered (100 x 100 m)
- Interaction between wind and multiple plumes is studied
- Dry neutral isothermal atmosphere (up to heights of 1000 m)
- Logarithmic wind velocity with specific ground roughness in atmospheric boundary layer
- Buoyancy force driven by variable density difference
- High Reynolds number k-ε turbulence model with specific surface roughness
- Composite radiosity model for radiation heat transfer (IMMERSOL in PHOENICS)

WILDFIRE case study: governing equations

3D mass, momentum and energy conservation equations

$$\frac{\partial \rho}{\partial t} + div(\rho U) = 0$$

$$\frac{\partial (\rho C)}{\partial t} + div(\rho C U - \rho D_{eff}\, gradC) = S_C$$

$$S_C : combustion\ model; D_{eff} = v_l / Sc_l + v_t / Sc_t ; Sc_l = D_l / v_l , Sc_t = 1$$

$$\frac{\partial (\rho u_i)}{\partial t} + div(\rho u_i U - \rho v_{eff}\, gradu_i) = -\frac{\partial P}{\partial x_i} + \rho g_i$$

$$i = 1,2,3; U = (u_1, u_2, u_3); v_{eff} = v_l + v_t ; v_t : turbulence\ model$$

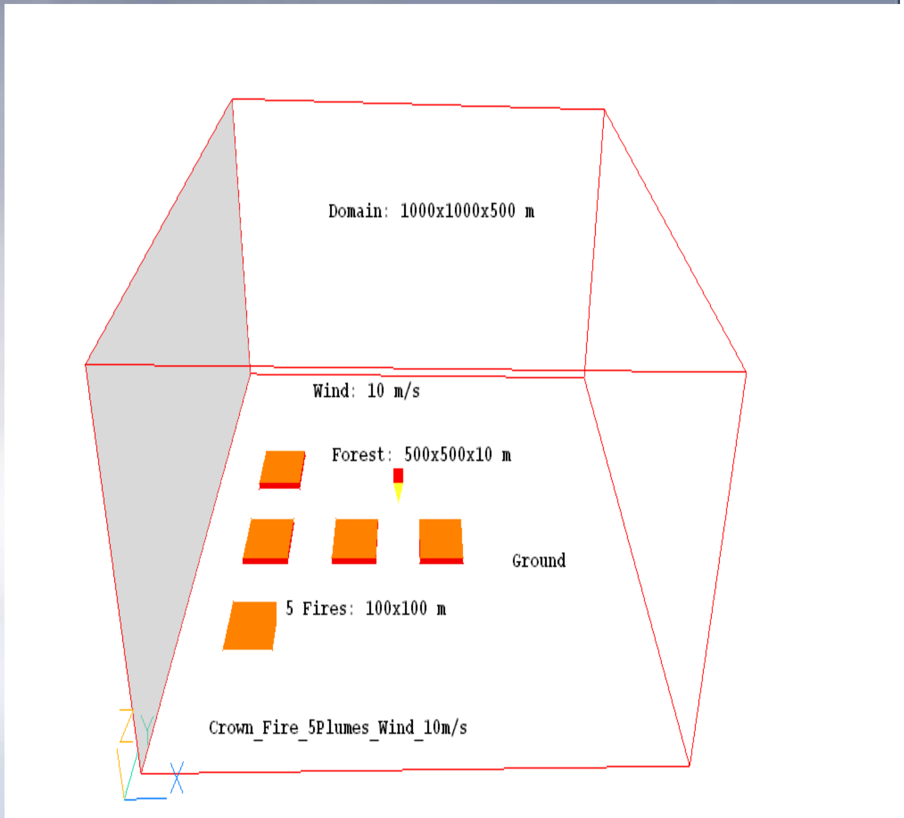
$$\frac{\partial (\rho c_p T)}{\partial t} + div(\rho c_p T U - \rho a_{eff}\, grad(c_p T)) = \frac{dP}{dt} + S_h$$

$$S_h : radiation / combustion\ models; a_{eff} = v_l / \Pr_l + v_t / \Pr_t ; \Pr_l = \rho v_l c_p / k_l ; \Pr_t = 1$$

WILDFIRE case study: fire geometry and energy

Geometry:

Domain: 1000 × 1000 ×500 m
Numerical grid size: 50 × 24 × 40
CFD run duration: 20 min
Forest size: 500 x 500 x 10 m
5 square wildfire plots
Single wildfire area: 100x100 m
Distance between fires: 100 m



FIRE heat and mass source:

Average fire temperature: T=1000°C
Head fire intensity: I=4000 kW/m

[1,2]: I=Hwr, H is net heat of combustion in kJ/kg (=18000 kJ/kg), w is weight of fuel consumed in kg/m2 and r is rate of spread in m/s (Byram's formula)

ICFME [2]: I is between 10000 to 90000 kW/m

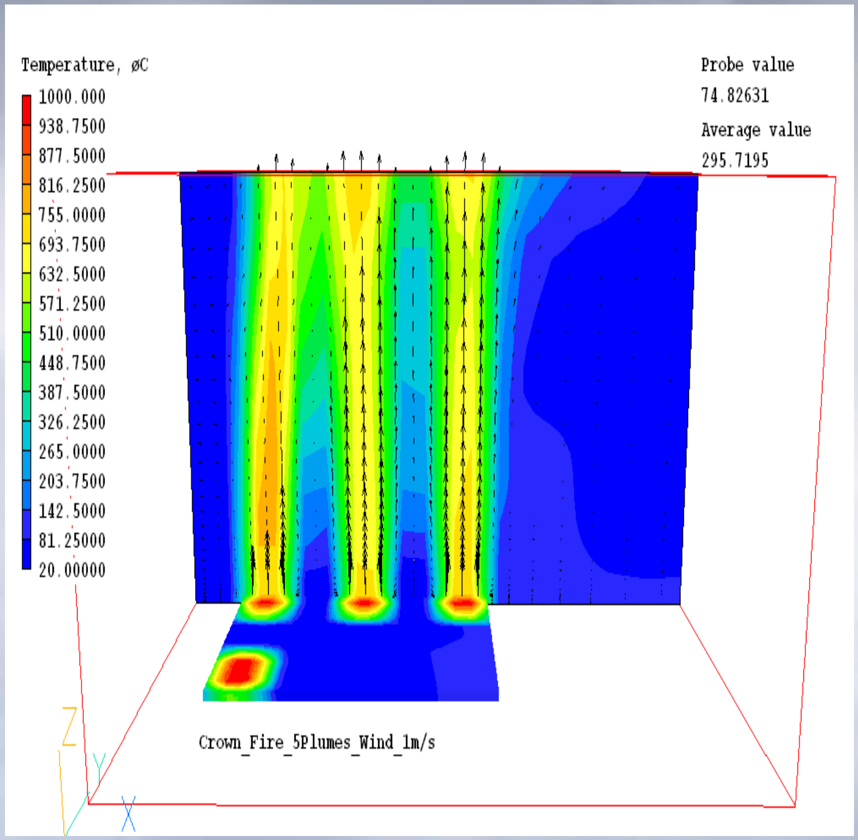
Vertical gas velocity at FIRE source [4]:

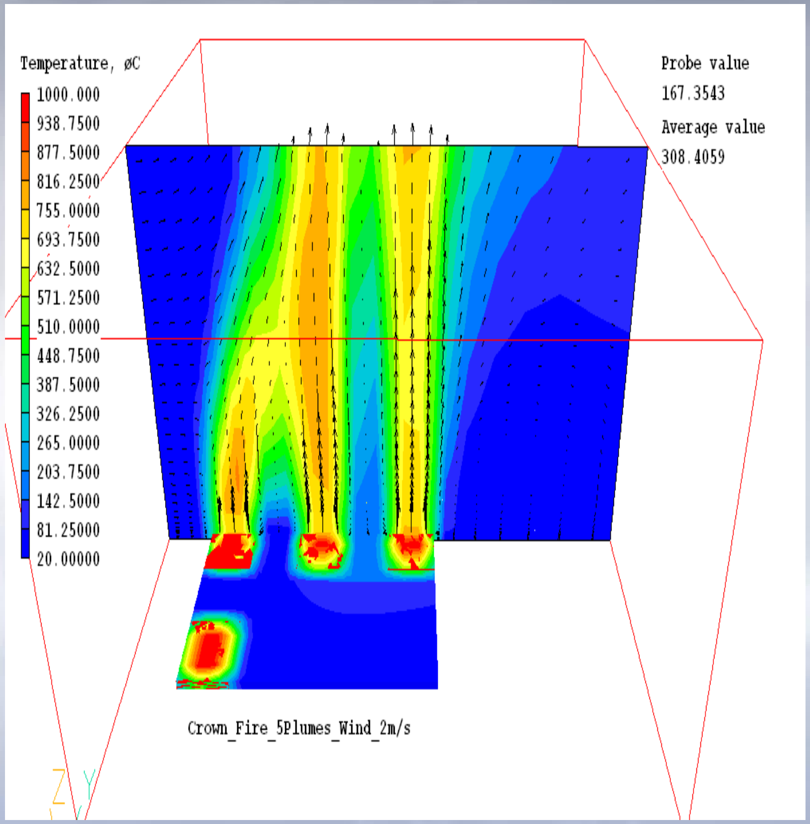
$V_f = 0.534*I^{0.334}$ with I in kW/m

$V_f = 50$ m/s at I=4000 kW/m

Original formula: $V_f = 1.3*I^{0.334}$ if I in kcal/(m*min)

WILDFIRE case study: results (plume-dominated wildfires)

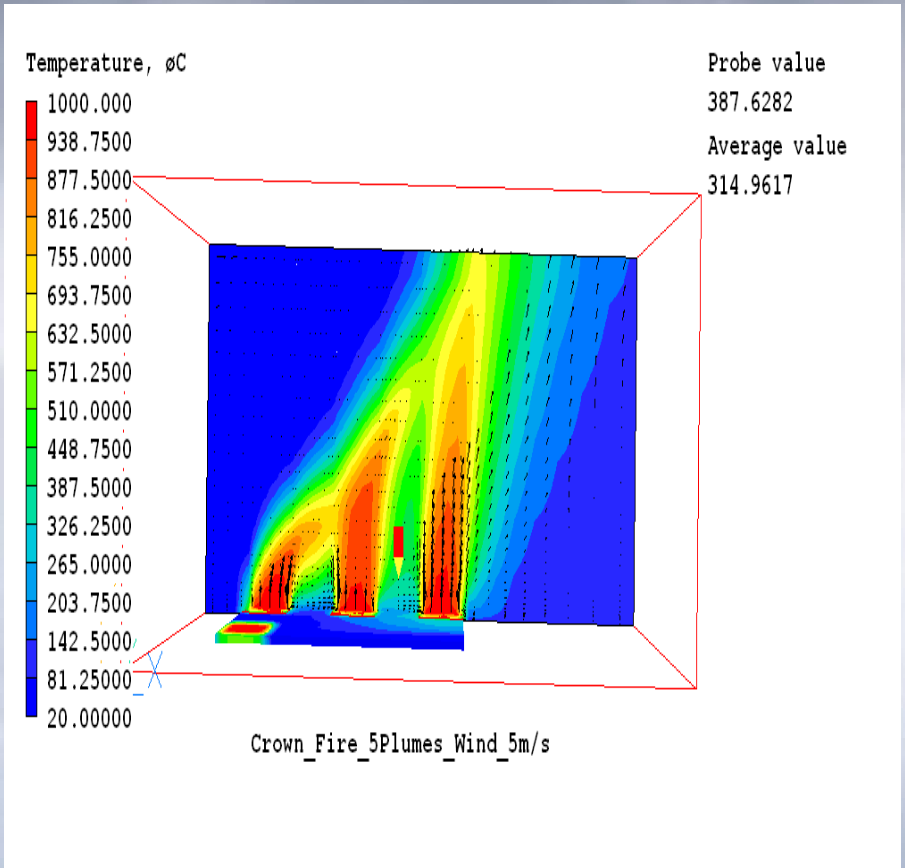


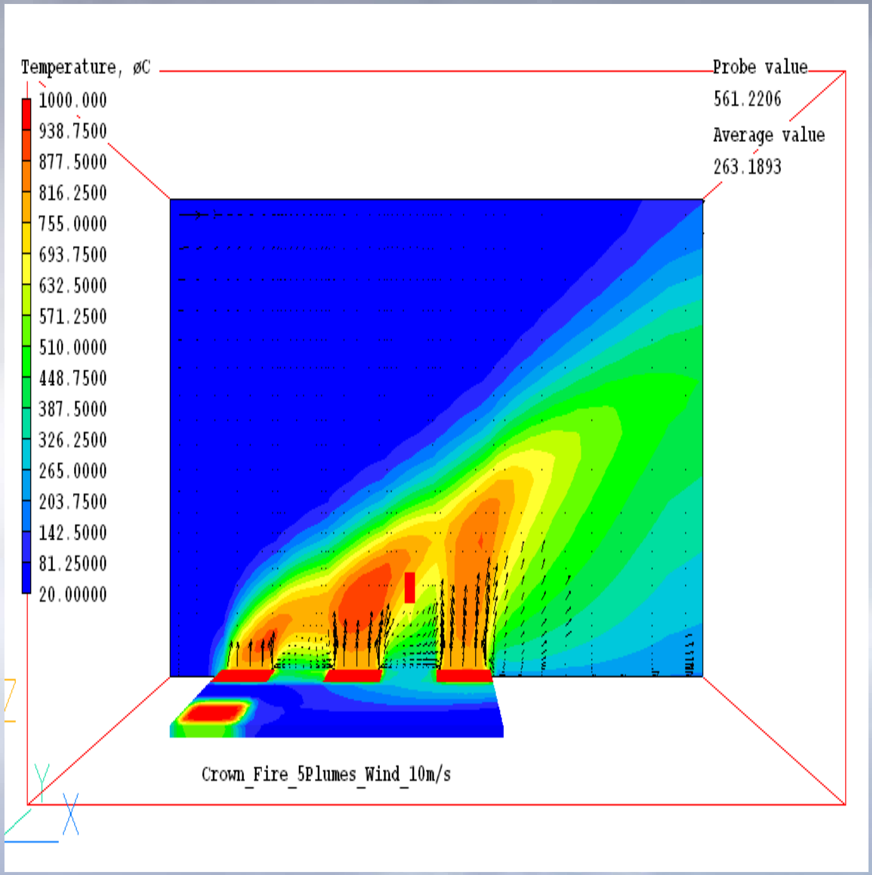


Thermal plumes for wind speeds of 1 and 2 m/s (convection numbers are 221 and 27.6): small effect of wind on plumes (plume-dominated wildfires)

Convection number [5], $N_c = 2gI/(\rho c_p T_0 (U_{wind} - r)^3$

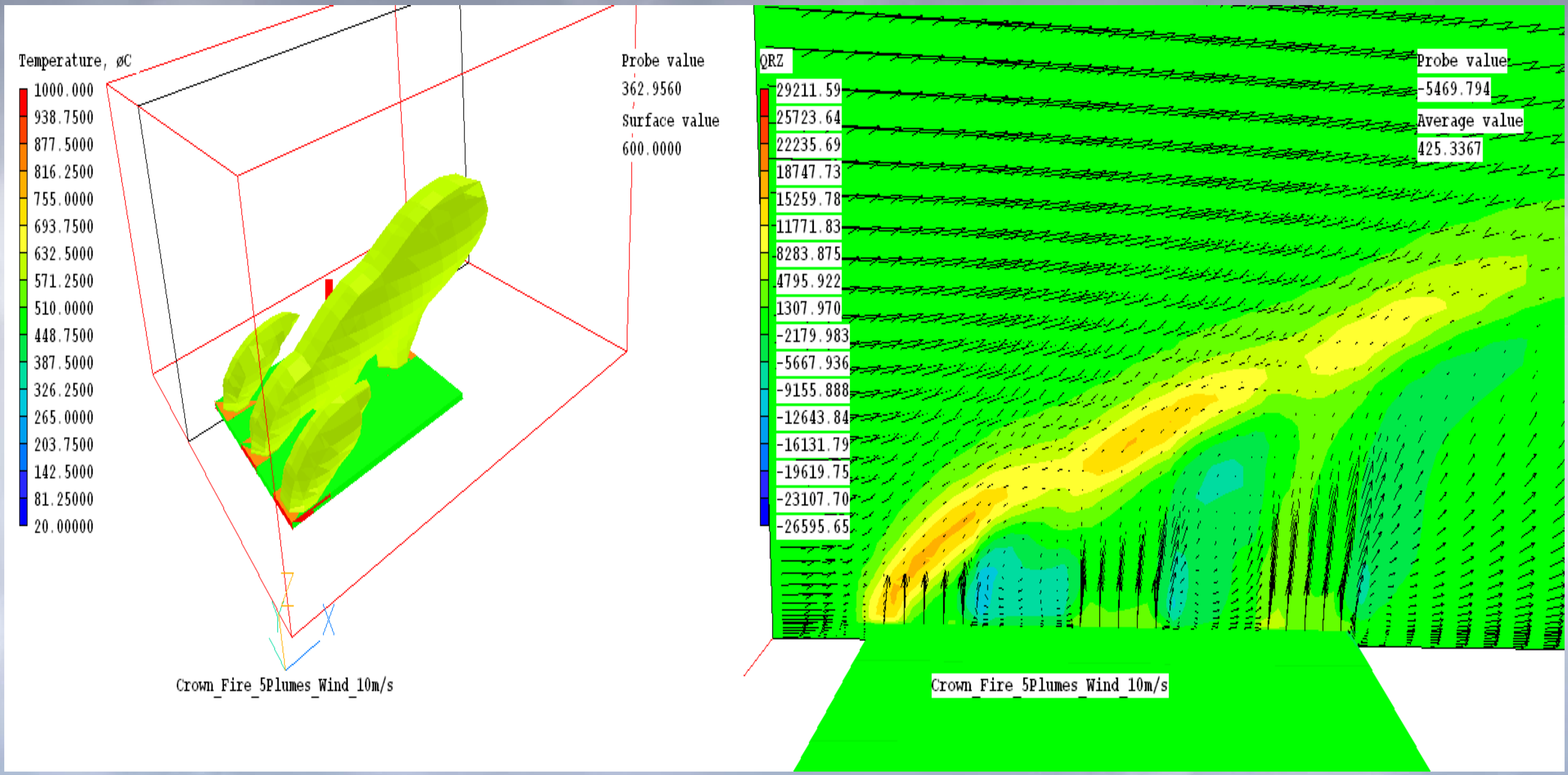
WILDFIRE case study: results (wind-driven wildfires)





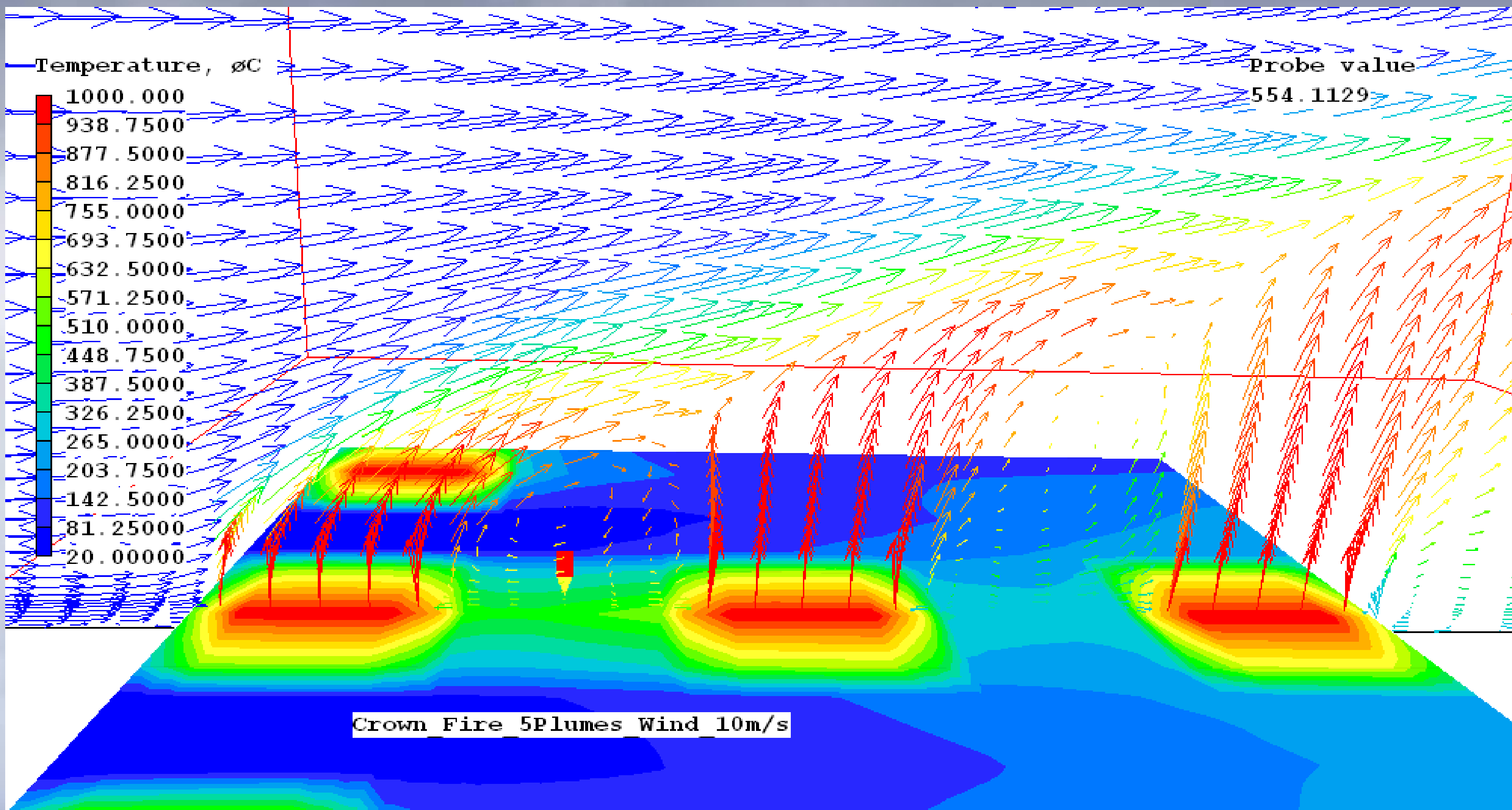
Thermal plumes for wind speeds of 5 and 10 m/s (convection numbers are 1.8 and 0.2): significant effect of wind on plumes (transition to wind-driven wildfires). Convection number [5], $N_c = 2gI/(\rho c_p T_0 (U_{wind} - r)^3$

WILDFIRE case study: results for 10 m/s wind (wind-driven wildfires)



600C iso-surface and vertical radiation flux (in W/m2) for wind speed of 10 m/s (wind-driven wildfires)

WILDFIRE case study: results for 10 m/s wind (wind-driven wildfires)



Gas velocity and temperature in the vicinity of multiple plumes for wind speed of 10 m/s (wind-driven wildfires); Pointer shows the most dangerous area between the fires (large vortex of high temperature gas)

WILDFIRE case study: summary

- General-purpose PHOENICS CFD software is customized for **modeling multiple plumes created by large crown wildfires**
- **Hydrodynamic and thermal interactions** between separate fires and wind are studied
- **Plume-dominated and wind-driven wildfires** are simulated
- CFD model can predict the 3D distributions of **pressure, velocity, temperature, smoke concentration, radiation heat fluxes and turbulence characteristics**
- **Future model developments**: model validation, accounting for fire spread (dynamic modeling), forest composition and chemical kinetics, complex terrain, atmospheric stratification and humidity, etc.

Summary

- **ACFDA research team** consisting of PhDs with 25+ years of experience in CFD, combustion and wildfire modeling (both academic and industrial) is developing advanced customized CFD models for wildfire modeling

- **Collaboration** between CFD experts and wildfire research community is required for developing and validating the robust, accurate and easy-to-use customized models of forest fires

- **Wide use of customized CFD models** by fire researchers and fire managers/engineers could be beneficial for wildfire modeling

Thank you!