Simplified Combustion Modeling Via Reduced-Physics Approximation In COMSOL Multiphysics®

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Abstract

Accurately resolving combustion normally requires solving large, stiff sets of elementary reaction equations. We present a reduced-physics approximation that replaces detailed chemistry with a single, smoothed reaction-rate expression {rr = kk*step1(T[1/K])*c} , where
kk is a tunable rate constant, c is the local mass fraction of the combustible mixture, and step1(T) is COMSOL's continuously differentiable Heaviside function, calibrated to mimic Arrhenius activation. The corresponding volumetric heat source is {Q = rr*Hu} with Hu the lower heating value. This formulation captures the essential coupling between species depletion and temperature rise while avoiding the stiffness and cost of multi-step kinetics.

Problem setup in COMSOL Multiphysics®:
The model is implemented with the Heat Transfer in Fluids and Transport of Diluted Species interfaces (Heat Transfer Module + Chemical Reaction Engineering Module). Temperature-dependent density and specific heat are imported from the Materials Library; gas thermal conductivity {k} is treated as a user parameter cond0. A 2D domain representing a generic gaseous layer is initialized with a narrow hot spot to trigger ignition.

Results:
Across 18 parameter combinations, the model reproduces key combustion behaviors at a fraction (< 5 %) of the computational cost of detailed chemistry. For high kk, high Hu, and low cond0 we observe dendritic, finger-like flame propagation reminiscent of wild-fire spread. Quantitatively, the front speed increases up to 60 % relative to planar cases, and the calculated fractal dimension rises from 1.00 to 1.35, indicating significant front roughening. Conversely, higher thermal conductivities damp this instability and yield smooth, quasi-planar fronts.

Conclusions and implications:
The reduced-physics approach retains essential thermo-chemical coupling while enabling rapid screening of material properties and operational envelopes. It is particularly useful for preliminary design of safety measures in low-conductivity gas environments (e.g., hydrogen-rich blends or forest under-canopies).

Figures used in the abstract

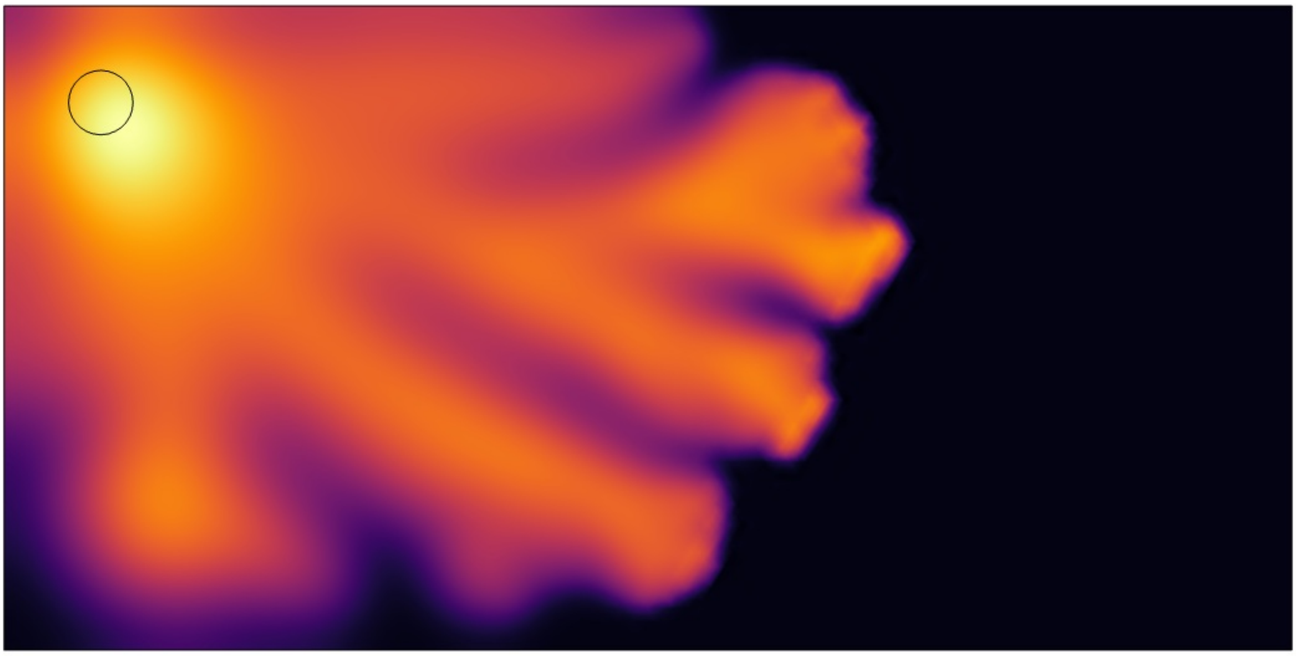

Figure 1 : Fractal Flame Front

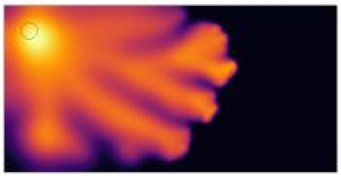

Figure 2 : thumbnail