# Studies with a Turbulent-Flame-Speed-Closure Model for Premixed Turbulent Flame Calculations

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**Abstract**

A computational model for turbulent premixed gaseous combustion is investigated, where the combustion process is modelled in terms of a single transport equation for a reaction progress variable. Turbulent closure of the source term of the progress variable is based on a model for the turbulent flame speed. In order to check the model, numerical results are compared with experimental data from a turbulent premixed V-shaped flame, where the conditions of the approaching turbulent flow and of the chemical processes have been varied separately and systematically. Additionally, three other relations from the literature for the turbulent flame speed have been tested within this turbulent flame speed approach. Furthermore, the influence of the formal structure of the reaction term is compared with that of other common approaches (gradient approach, parabolic approach, eddy dissipation concept). While for the gradient approach the calculated flame shape agrees with the experimentally found straight lines, for the other approaches a concave bounded flame shape is found. This can be understood by analyzing the reaction rate integral across the flame brush. If the length scale of the parabolic approach would be proportional to the flame brush thickness, also here width-independence could be reached, requiring, however, additional modelling equations.

## Numerical model and comparison with experiment

A computational model for turbulent premixed gaseous combustion is investigated, where the combustion process is modelled in terms of a single transport equation for the mean reaction progress variable $\overline{c}$, being defined as the normalized mass fraction of products ($c$ = 0 in the unburnt mixture and $c$ = 1 in the products). The source term of the progress variable is modelled with

$$\overline{w}_c = \rho_u \, s_T \left|\nabla \overline{c}\right| \qquad (1)$$

where the turbulent flame speed $s_T$ includes physico-chemical properties and local turbulence parameters of the combustible mixture [1], while the coupling to the transport equations of the flow field is done with the density calculated from the reaction progress variable. These equations have been implemented as subroutines into a computational fluid dynamics (CFD) code [2,3].

In order to check the model, numerical results are compared with experimental data from a turbulent premixed V-shaped

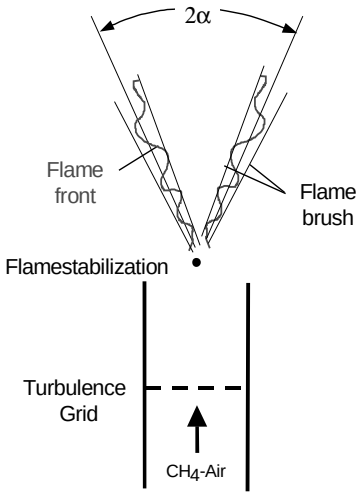


**Fig. 1:** Experimental setup of turbulent V-flame.

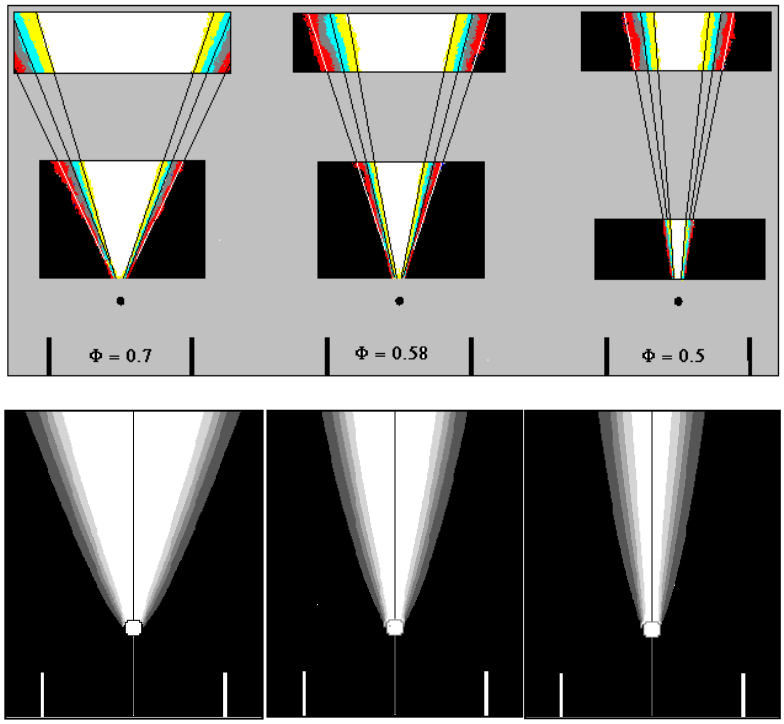


**Fig. 2:** Mean reaction progress variable $c$ of turbulent premixed V-shaped flames in the plane perpendicular to the flame holder for different stoichiometric ratios $\Phi$ . Upper line, experimental data, determined with planar laser-induced Rayleigh scattering ($\overline{c}$ = probability to find burnt gas). Lower line, calculated flames.

flame (Fig. 1) which is stabilized on a 2 mm diameter wire, situated 10 mm above the burner exit (width 40 mm). The conditions of the approaching turbulent flow and of the chemical processes have been varied separately and systematically with exit velocities between 1.8 and 3.1 m/s, turbulent Reynolds numbers between 45 and 87 and lean methane-air mixtures with stoichiometric ratios between 0.5 and 0.7 [4,5]. Note that the decrease of the density in the reaction zone strongly influences the streamlines of the mean flow-field. Therefore the flame location of the V-shaped flame is very sensitive to this effect. This is a challenge to correct flame modelling, and constant density models would fail to predict the flame angle. Additionally, the width of the flame zone increases with height, and the influence on this parameter can be investigated. Using the flame speed relation of Zimont (see below) the comparison between calculation and experiment shows that the calculated flame location and flame width fit well with the experimental data for the different flow rates and equivalence ratios, without tuning on fitting constants (Fig. 2).

## Comparison with other turbulent flame speed relations

Besides the flame speed relation of Zimont (eq. (2)), three other relations for the turbulent flame speed have been tested, two being determined from experimental data (eq. (3), (4)), one from theoretical argumentations with some 'tentatively' fixed fit constants (eq. (5)):

Zimont [2]: $$\frac{s_T}{s_L} = A \cdot Pr^{1/4} \cdot Re_t^{1/4} \cdot \left(\frac{u'}{s_L}\right)^{1/2} \quad \text{with} \quad A = 0.52 \tag{2}$$

Gülder [6]: $$\frac{s_T}{s_L} = 1 + 0.62 \cdot Re_t^{1/4} \cdot \left(\frac{u'}{s_L}\right)^{1/2} \tag{3}$$

Liu-Ziegler-Lenze [7]: $$\frac{s_T}{s_L} = 1 + 0.435 \cdot Re_t^{0.44} \cdot \left(\frac{u'}{s_L}\right)^{0.4} \tag{4}$$

Peters [8]: $$\frac{s_T}{s_L} = -\frac{a}{2}A + \left(\left(\frac{a}{2}A\right)^2 + a \cdot A \cdot \frac{u'}{s_L} + a + 1\right)^{1/2} \quad \text{with } A = \frac{Re_t}{u'/s_L} + 1,\ a = 0.547 \tag{5}$$

with the Prandtl number $Pr = \nu / a = 0.71$, the kinematic viscosity $\nu$, the thermal diffusivity $a$, the turbulent Reynolds number $Re_t = u' \, l_x / \nu$, the integral length scale $l_x$, the root-mean-square velocity fluctuation $u'$, and the laminar burning velocity $s_L$.

Aside of the mentioned relation (2) the relation (6) fits quite well with the experimental data (Fig. 3), while the use of the experimental determined flame speeds results in significantly overestimated flame angles (relation (4) is not shown and gives even higher flame angles). Obviously, the unreflected use of experimental flame speed correlations, where the flame speed is correlated to the unburned flow conditions just ahead of the flame front, is leading to erroneous results in the present approach, since for the calculations a somewhat increased resulting flame speed inside the flame brush is effective instead.

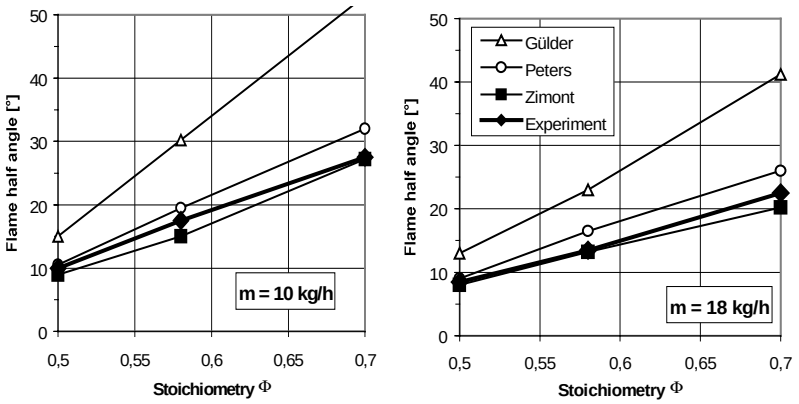


**Fig. 3:** Comparison between experiment and calculation**.** Flame location (flame half angle $\alpha$ ) as a function of flow rate and stoichiometry. Calculation with different turbulent flame speed relations.

## Influence of the reaction term structure

In an additional study [4] the influence of the formal structure of the reaction term ( $\overline{w}_c \sim |\nabla \overline{c}|$ ) is compared with that of the common parabolic approach ( $\overline{w}_c \sim \overline{c} \cdot (1 - \overline{c}) / L_y$, proposed e.g. in the Bray-Moss-Libby model [9] and in other approaches). While for the gradient approach the calculated flame shape agrees with the experimentally found straight lines, for the parabolic approach a concave bounded flame shape is found for constant length scale $L_y$ (Fig. 4). This can be understood by analyzing the reaction rate integral across the flame brush. In the first case this integral is width-independent. In the second case the reaction rate integral is proportional to the width of the turbulent flame brush instead, which does not make sense for a flame with this kind of topology. If the same analysis is applied to the reaction term of the eddy-dissipation-concept [10], which

for the case of simple premixed flames has the form $\overline{w}_c \sim \min[(1-\overline{c}), \overline{c}, \gamma]$ with a constant $\gamma$ , also here the reaction rate integral is proportional to the width of the flame brush.

For the parabolic approach a width-independence could be reached, if the length scale $L_y$ would be proportional to the flame brush thickness, requiring, however, additional modelling equations.

The model has also been applied for calculations of larger turbulent premixed flames, a turbulent premixed Bunsen-type flame of 100 kW [2] and a premixed swirl burner of the type of a gas turbine [11], showing that the agreement between calculation and experiment is reasonable well for these flames of semi-industrial size.

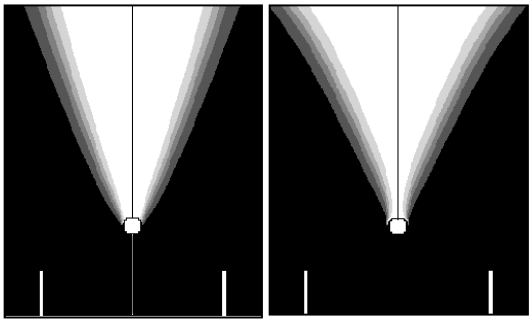

**Fig. 4:** Calculated flame contour with the gradient approach (left side) and the parabolic approach (right side), where the contour differs from the experimental shape. ($\Phi$ = 0.7)

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