# LOW-ORDER MODELING OF IGNITION IN ANNULAR COMBUSTORS

**L. C. C. Mesquita[1], R. Ciardiello[1], E. Mastorakos[1]**

[1] Department of Engineering, University of Cambridge, Cambridge, UK
lc796@cam.ac.uk

## Abstract

The SPINTHIR model, which is a Lagrangian stochastic low-order model for ignition validated and applied to several premixed and non-premixed cases, is modified in this paper to improve the numerical prediction of the flame light-round process in premixed annular combustors. This work proposes to take into account Flame Generated Turbulent Intensity (FGTI) and to impose the tubulent flame speed to the flame particles using expressions from the literature to address the current limitations in SPINTHIR. For this, using RANS CFD results as an input, the model was applied to simulate the ignition transient in a premixed, swirled bluff body stabilized annular combustor to characterize the light-round time, both in stable conditions and close to the stability limits. Several cases were analyzed, where flame speed and fuel are varied and light-round times are compared to experimental results. The proposed modifications increased the precision of the light-round time predictions, suggesting that FGTI may be an essential phenomenon to be modeled. The SPINTHIR model coupled with the Bray turbulent flame speed expression resulted in an average error of $15\%$, a maximum error of $26\%$ and minimum error of $1\%$ for the explored range of parameters. This is an attractive feature considering the low computational cost of these simulations, which take on average $75\,\mathrm{min}$ per simulation in a single core of a local workstation.

## 1 Introduction

Being able to predict with good confidence the ignition performance of an aeronautical combustor is a central step in the design process of the engine. More specifically, new burners are being designed to operate in full lean regime, introducing new challenges and stressing the importance of correctly evaluating the interactions between turbulence and flame, that introduces stochasticity and may affect the flame front propagation, risking, for example, Lean Blow-off. Being able to account and assess the impact of this intrinsic variability on the ignition is, then, a core step in predicting the ignition performance of the engine. One of the possible approaches to achieve this goal is to employ a low-order tool, where multiple runs can be performed to account for the stochasticity of the parameters controlling the ignition problem with low computational cost and high statistical representation. The challenge becomes, then, to guarantee good accuracy with such a low-order model. The SPINTHIR model, a Lagrangian stochastic low-order model for ignition, has been validated and applied to both premixed and non premixed cases canonical cases [15, 18] producing very accurate results. However, it a work by Ciardiello [4] applying SPINTHIR to reproduce the light-round process in an annular combustor close to stability limits showed that SPINTHIR largely over-predicted the light-round time. Furthermore, SPINTHIR did not capture the effect of changing the laminar flame speed on the flame front propagation speed and on the light-round time.

The objective of this work thus is to propose two improvements to the SPINTHIR model aiming to capture the laminar flame speed effect on the flame front propagation and to result in a better estimation of light-round time. The simulations will be carried out on a lab-scale annular combustor with premixed bluff-body stabilized flames (each individual burner having a geometry similar to the one used in [15]) and the results will be compared with data coming from experiments. Several cases are analyzed, where flame speed and fuel are varied and light-round times are compared to experimental results. The paper is structured as follows: fist the burner, studied cases and non-reacting CFD are described. Then, the SPINTHIR model is introduced, along with the proposed modifications. Finally, results are presented and discussed.

## 2 Studied cases and non-reacting CFD input

The calculations were performed on the Cambridge annular combustor, a premixed, swirled, bluff body stabilised annular combustor (see Refs. [6, 7, 5] for details). In this study, the capabilities of SPINTHIR in capturing the light-round time are evaluated in different scenarios. Two main parameters are varied, following the same procedure as the experiments [6, 5]: the laminar flame speed and the fuel type, modifying the unburnt-burnt gases density ratio. Table 1 summarizes the analyzed cases. The fuels employed are methane and ethylene and the swirl number is $S_n =$

Table 1: Flow conditions of the test cases

| Fuel | # burners | $U_{mix}$ | $\phi$ | $S_L$ (cm/s) | Spark location $[x/D]$ |
|---|---|---|---|---|---|
| $CH_4$ | 18 | 16 | 0.75-0.85-1 | 24-30-36 | 0.5 |
| $C_2H_4$ | 18 | 16 | 0.58-0.62-0.67-0.77-0.80-0.82-0.84-0.86-0.88-0.90 | 24-30-36-47-50-52-54-56-58-59 | 0.5 |

1.22 [19].

The CFD flow fields needed for the SPINTHIR calculations were obtained using the Rolls-Royce proprietary finite volume code PRECISE-UNS. RANS simulations were performed on the annular burner to capture the time-averaged flow field. The numerical mesh used is hexa-dominant and unstructured, refined inside the swirler, to correctly resolve the flow field in the small passages. A mass flow rate of air of $\dot{m} = 2.59g/s$ is specified, resulting in the $u_{bulk} = 16m/s$ at the chamber entrance. Since the case is fully premixed, the equivalence ratio is then set to the desired value inside the whole chamber before running the SPINTHIR simulations. A large cylindrical region is added at the exit of the chamber to mimic the atmosphere. Pressure is 1 atm and temperature is set to 293K and walls are considered adiabatic, as SPINTHIR does not consider thermal exchanges with the walls.

# 3 Methods

## SPINTHIR model

The low-order model SPINTHIR [15] is used to perform ignition simulations. Using a time-averaged non-reacting CFD flow field, it models the flame motion by using Lagrangian "flame particles". These are convected over the flow field, following a random walk based on a Langevin model [17] described by the following equations:

$$dX_{p,i} = U_{p,i}dt \tag{1}$$

$$dU_{p,i} = -\left(\frac{1}{2}+\frac{3}{4}C_0\right)\omega_p(U_{p,i}-\tilde{U_i})dt+(C_0\epsilon_p dt)^{1/2}N_{p,i} \tag{2}$$

where $dX_{p,i}$ is the particle displacement in the time interval $dt$, $\tilde{U_i}$ is the local Favre averaged velocity, $C_0$ is a constant equal to 2, $\omega_p = u'_p/L_{turb,p}$, $u'_p$ is the velocity fluctuation, $L_{turb,p}$ is the turbulent length scale, $\epsilon_p$ is the local rate of dissipation of turbulent kinetic energy and $N_{p,i}$ is a random variable following a Gaussian distribution with zero mean and unity variance, which introduces the stochasticity in the process.

As the flame particles are convected through the domain, their propagation are evaluated each time they move between mesh cells depending on a Karlovitz number extinction criterion. This number is defined based on the correlation proposed by [2] and calculated for each flame particle at each time instant:

$$Ka_p = 0.157\left(\nu\frac{(u'_p)^3}{L_{turbo,p}}\right)^{1/2}\frac{1}{{S_{L,p}}^2} \tag{3}$$

where $\nu$ is the kinematic viscosity of the mixture, $u'_p$ is the rms velocity, $L_{turbo,p}$ is the turbulence length scale and $S_{L,p}$ is the flame laminar speed. If in a given cell a flame particle has a $Ka_p$ number smaller than a critical Karlovitz reference value, a new flame particle is created and the flame propagates. Otherwise, the flame particle is extinguished. Multiple simulations are performed in this way to evaluate the flame propagation and ignition probability.

## The turbulent flame speed mismatch and proposed modifications

R. Ciardiello [4] showed that for the simulation of premixed combustion cases the SPINTHIR model underestimates the turbulent flame speed and, thus, the light-round time. Furthermore, the light-round time calculated does not scales with the laminar flame speed as found in the experiments, consequence of the laminar flame speed not being a parameter of the model. Indeed, the baseline modeling for SPINTHIR relies on the N. Peters [16] assumption that the turbulent flame speed is equivalent to the velocity fluctuations: $\frac{S_T}{S_L} = \frac{u'_{rms}}{S_L}$. In addition, the original SPINTHIR modeling is only based on the non-reacting turbulence, and thus may miss some flow modifications created due to the expansion during the light-round process [12]. This work proposes two modifications to address these limitations.

First, Flame Generated Turbulent Intensity (FGTI) will be considered. Kuo *et al.* [12] defined FGTI as being caused by the velocity jump on the flame front:

$$\overline{u'^2_{fg}} + \overline{v'^2_{fg}} + \overline{w'^2_{fg}} = \left(\frac{\rho_u}{\rho_b} - 1\right)^2 S_L^2 \tag{4}$$

where $\overline{u'^2_{fg}}$, $\overline{v'^2_{fg}}$ and $\overline{w'^2_{fg}}$ are respectively the average of each velocity component fluctuation, $\rho_u$ and $\rho_b$ are the density of unburnt and burnt gases (respectively), and $S_L$ is the laminar flame speed. This expression is used to calculate the corresponding flame generated turbulent kinetic energy that will be then added to the non-reacting turbulent kinetic energy calculated by the CFD.

Second, to attempt to correctly capture turbulent flame speed (and hopefully the experimental light-round time), known expressions for the turbulent flame speed will be employed over the particles' displacement velocity. This will be done by modifying the magnitude of the flame particle velocity vector (but keeping its direction) issued from the Langevin equation. The velocity vector is normalized and then multiplied by a turbulent flame speed expression found in the literature ($S_T$):

$$U_{p,i} = \frac{U_{p,i}}{\sqrt{U_{p,1}^2 + U_{p,2}^2 + U_{p,3}^2}} \times S_T \tag{5}$$

In practice, this means using the Langevin equation to create a turbulent motion for the particles, as the direction of motion issued by the Langevin equation is not modified, while imposing that all particles move with the turbulent flame speed. Although this may fail to reproduce a theoretically-rigorous turbulent mixing process, in the spirit of an engineering tool the approximation may be acceptable.

Additionally, the expression retrieved by Ciardiello [4] by correlating the laminar flame speed with the flame front propagation speed after the various experiments is also employed:

$$S_T = \frac{\rho_u}{\rho_b}(3.82 S_L + 1.33) \tag{6}$$

As this expression comes directly from the experimental results that are here evaluated, it should give sensible results. It is used then as a mean of validation of the modeling framework expressed by Eq. 5. Additionally, the use of this expression will help understand if imposing an expression derived from the flame front propagation on the individual motion of the flame particles would, in the end, result in the same flame front propagation in the SPINTHIR model. Since this expression already takes into account the gases expansion, it will not be used along with the FTGI model. The same applies for the two Ishisuka *et al.* [10] models. All other turbulent flame speed expressions are used along with the increased turbulent kinetic energy by FGTI.

The Karlovitz criterion for flame extinction is left unchanged.

# 4 Results

## Evaluation of turbulent flame speed expressions

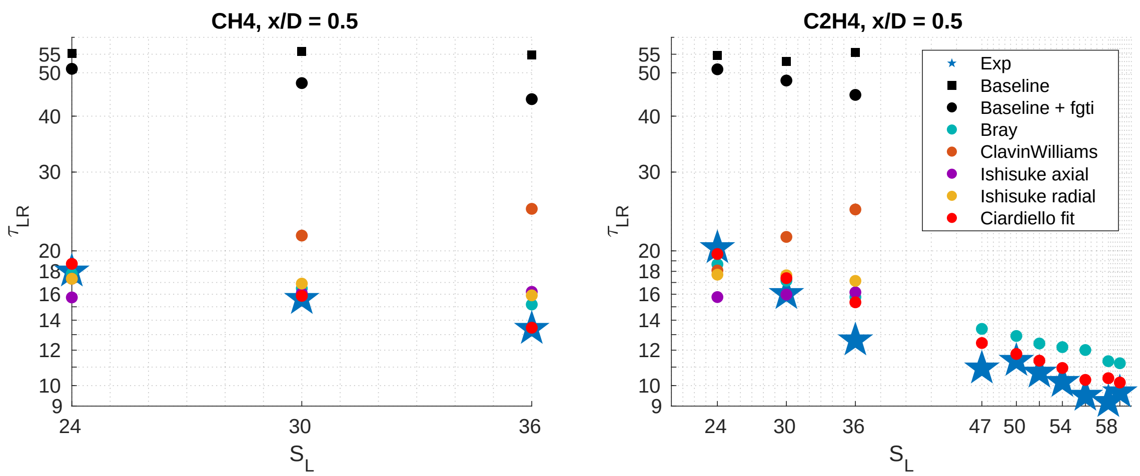
On the first set of calculations, all the expressions in Tab. 2 were simulated, along with the baseline SPINTHIR without considering FGTI (original model) and with FGTI, for a reference case using methane and a laminar flame speed of $S_L = 24\,\mathrm{cm/s}$. This first assessment was done to evaluate the expressions and framework in a single case, before trying to capture the influence of laminar flame speed on the light-round time. The results are summarized in Tab. 2. First, one can see that the Baseline SPINTHIR model overestimates the light-round time by approximately a factor of 3. While considering FGTI improves the results, it only does slightly, showing that the flow fluctuation itself does not suffice to impose the correct turbulent speed to the flame particles. The next result that must be analysed is the use of the macroscopic expression derived from Ciardiello's experiments [4]: it results in an excellent agreement. While this might seem obvious at a first look, this shows that the framework of using the Langevin model to generate turbulent motion, while a turbulent flame speed expression ensures the correct flame propagation speed, is able to produce sensible results. However, it would be interesting now to find a general equation that could be able to reproduce the experimental data. Looking at the outcomes of the simulations employing expressions from the literature for the turbulent flame speed, one can see that only four are close to the experimental one: Clavin *et al.* [8], Bray [3] and the two expressions from Ishisuka *et al.* [10]. While the reasons why only these four expressions produce good predictions in this case are out of the scope of this study, these four expressions will then be used on the second part of the study (along with the baseline SPINTHIR and Ciardiello's expression) to analyse the impact of changing the laminar flame speed and density ratio on their prediction capabilities.

## Effect of laminar flame speed variation

The three laminar flame speed cases for methane are summarized in Fig. 1a. First analysing the baseline SPINTHIR, one can see that the result found by Ciardiello [4] is here retrieve: the baseline model cannot capture the effect of laminar flame speed over the light-round time. However, considering FGTI insert the laminar flame speed effect into the model, reducing the light-round time as the laminar flame is increased, as expect. Despite introducing the correct trend, the baseline SPINTHIR with FGTI still overestimates the light-round time in all cases, repeating last section result. Also, when Ciardiello's turbulent flame speed expression is applied, the model gives excellent predictions, confirming that this framework is also capable

Table 2: Turbulent flame speed equations from the literature and resulting light-round time from SPINTHIR simulation

| Reference | Equation | Light-round time [ms] |
|---|---|---|
| Experiments | - | 18.0 |
| Baseline | - | 55.27 |
| Baseline with FGTI | - | 51.02 |
| Ciardiello [4] | $S_T = \frac{\rho_u}{\rho_b}(3.82 S_L + 1.33)$ | 18.21 |
| Damköhler [9] | $\frac{S_T}{S_L} \approx Re_L^{1/2}$ | 31.26 |
| Abdel-Gayed et al. [1] | $\frac{S_T}{S_L} \approx Re_L^{0.24}$ | $> 80$ |
| Libby et al. [13] | $\frac{S_T}{S_L} = 2.1 \left(\frac{u'_{rms}}{S_L}\right)$ | 65.11 |
| Clavin et al. [8] | $\frac{S_T}{S_L} = 1 + \left(\frac{u'_{rms}}{S_L}\right)^2$ | 17.23 |
| Liu at al. [14] | $\frac{S_T}{S_L} = 1 + 5.3 \frac{u'_{rms}}{S_L^{0.5}}$ | 51.90 |
| Bray [3] | $\frac{S_T}{S_L} = 7.25 \left(\frac{u'_{rms}}{S_L}\right)$ | 16.79 |
| Kerstein et al. [11] | $\frac{S_T}{S_L} = 1 + \left(\frac{u'_{rms}}{S_L}\right)^{4/3}$ | 67.84 |
| Ishisuka et al. (axial) [10] | $S_T = \left(\frac{\rho_u}{\rho_b} S_L^2 + u_{\theta,max}^2\right)^2$ | 15.74 |
| Ishisuka et al. (radial) [10] | $S_T = S_L + u_{\theta,max}\left(1 + \frac{\rho_u}{\rho_b}\right)^{0.5}$ | 17.33 |




(a)

(b)

Figure 1: Evolution of light-round time $\tau_{LR}$ in function of the laminar flame speed $S_L$ for (a) methane and (b) ethylene. For the ethylene case, all models were simulated only for the $S_L = 24, 30, 36\,\mathrm{cm/s}$ cases, while the Bray model and Ciardiello's fit were simulated for the ten laminar flame speed velocities to further evaluate the impact of increasing the laminar flame speed.

of capturing the laminar flame speed effect. On the literature expressions, however, various different results are observed. Clavin *et al.* [8] expression presents a laminar flame speed trend opposite to the one observed during the experiments. Indeed, looking at Clavin *et al.* [8] equation, the turbulent flame speed is inversely proportional to the laminar flame speed. Both Ishisuka *et al.* [10] expressions also do not result in a correct scaling of the light-round time with the laminar flame speed, as they are barely modified by it. In these expressions, the tangential velocity of the flow is the piloting phenomenon in the turbulent flame speed, thus shadowing the laminar flame speed impact. Finally, the Bray modeling [3] produced an excellent agreement with the experimental results for the three laminar flames. It must be noted that the Bray model does not take into account the laminar flame speed, as the baseline SPINTHIR model. In both cases the effect from the laminar flame speed is translated only through FGTI, which is then accounted directly by the $u'_{rms}$ in their expressions and imposing the laminar flame speed effect on the light-round time. This is enough then for the model using Bray's expression to reproduce well both light-round time and the scaling with the increase in laminar flame speed.

The results for ethylene, shown in Fig. 1b, confirm the previously discussed for methane. As the Bray [3] and Ciardiello [4] models produced the best results, they were used to simulate the higher laminar flame speed cases. These results showed that, while Ciardiello's expression continued to scale very closely to the experiments (as it was derived from them), the Bray model [3] started to present a consistent overestimation of the light-round time. Nevertheless, these results show that Bray model reproduced well the scaling, highlighting the importance of modeling FGTI. Indeed, one interesting conclusion found during the experiments was the small impact gaseous expansion had on the light-round time, compared to laminar flame velocity [5]. Thus, it is particularly interesting to verify that the Bray model is able to reproduce this trend, as the gaseous expansion impacts the calculated light-round time also only through FGTI. Finally, the Bray model gave an overall very good prediction of light-round time for the explored range of parameters with an average error of $15\%$, a maximum error of $26\%$ and minimum error of $1\%$, which is an attractive feature considering the low computational cost of these simulations (average of $75\,\mathrm{min}$ per simulation in a single core of a local workstation).

# 5 Conclusions

The low order model SPINTHIR was applied to an annular premixed combustor to predict light-round time. It was found in previous studies [4] that the baseline model overestimated the light-round time and did not capture the effect of laminar flame speed on the flame front propagation. Two improvements of the model were proposed in this work and evaluated: First, as the SPINTHIR model is based on the non-reacting flow field, Flame Generated Turbulent Intensity (FGTI) was calculated and added to the turbulent intensity calculated from the non-reacting CFD. Second, the Langevin model used to generate the turbulent motion of the flame particles was modified to impose the turbulent flame speed over the flame particles, using several expressions from the literature. Additionally, an expression interpolated from the experimental results by Ciardiello [4] was also used to test the framework against the experimental data.

The modified SPINTHIR model using Ciardiello expression for the turbulent flame speed produced an excellent agreement with the experimental results, showing that the proposed framework is capable of retrieving the experimental results and trends. From the simulations using turbulent flame speed expressions coming from the literature, only Bray's expression [3] was able to produce, at the same time, a good agreement with the experimental results for all the range of parameters (an average error of $15\%$, maximum error of $26\%$ and minimum error of $1\%$) and the correct effect of laminar flame speed over the light-round time. Furthermore, the good agreement obtained from Bray [3] emphasises the important of modeling FGTI, as Bray's expression relies only on the scaling of flow $u'_{rms}$ with the laminar flame speed. The present results show that its possible to have a good estimation in light-round time with a low order model and an *a priori* expression for turbulent flame speed with very low computational cost, as each simulation would take on average $75\,\mathrm{min}$ to run in a single core of a local workstation.

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