Impact of Flame-Generated Turbulent Intensity and Flame Speed on the Low-Order Modelling of Light-Round

Léo C. C. Mesquita1 · Roberto Ciardiello1 · Epaminondas Mastorakos1

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Abstract
A previously-developed low-order Lagrangian stochastic model for ignition of premixed and non-premixed flames is modified in this paper to improve the numerical prediction of the light-round process in premixed annular combustors. The model refinements take into account Flame-Generated Turbulent Intensity (FGTI) and impose a turbulent flame speed correlation to the flame particles using expressions from the literature. For this, using RANS CFD results as an input, the model was applied to simulate the ignition transient in a premixed, swirled bluff body stabilised annular combustor to characterise the light-round time, both in stable conditions and close to the stability limits. Several cases were analysed, where flame speed and fuel were varied and light-round times were compared to experimental results. The proposed modifications improved the accuracy of the light-round time predictions, suggesting that FGTI may be an important phenomenon to be modelled. This modified model coupled with dilatation and the Peter’s assumption for the turbulent flame speed resulted in considerable improvement for the light-round time calculation for the explored range of parameters. This is an attractive feature considering the low computational cost of these simulations, which can be run in a single core of a local workstation. The improved model can help gas turbine engineers assess the ignition behaviour of annular combustors early in the design process.

Keywords Light-round · Low-order modelling · Annular combustor · SPINTHIR · Ignition


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 lean regime, which introduces new physical phenomena and challenges for the ignition. High-altitude relight is particularly difficult for the engine due to low pressure and temperature (Lieuwen and Yang 2013), making extremely important to guarantee the ignition success in these conditions. Furthermore, the stochastic nature of the interactions between turbulence and flame may affect the flame front propagation during all phases of the ignition transient. Therefore, being able to account and assess the impact of this intrinsic variability on the ignition is important for predicting the ignition performance of the engine.

The ignition process can be broken down into four phases (Mastorakos 2009, 2017): (i) flame kernel formation, (ii) flame growth, (iii) flame stabilisation over a single burner and (iv) burner-to-burner propagation, commonly called “light-round” (as in practice aero-engines are composed of multiple burners often arranged in an annular configuration (Lefebvre and Ballal 2010)). Even if all phases of ignition are equally complex and relevant, the study of the light-round process introduces an additional challenge, as it requires a full multi-burner geometry. This increases the cost of both experimental and numerical studies of this process. Experimentally, light-round has been studied in premixed (Bourgouin et al. 2013; Machover and Mastorakos 2017; Xia et al. 2019; Ciardiello et al. 2020), non-premixed (Machover and Mastorakos 2016, 2017) and spray (Barré et al. 2014; Marrero-Santiago et al. 2019; Prieur et al. 2017; Lancien et al. 2017; Prieur et al. 2018) burners, in linear or annular configurations. Numerically, Large-Eddy Simulations (LES) have been used to simulate the light-round process in realistic geometries of aero-engines (Boileau et al. 2008; Philip et al. 2015; Lancien et al. 2017; Puggelli et al. 2019), shedding new light on the mechanisms of the flame front propagation, complementing the available experimental data. However, in both experimental or high-fidelity numerical studies, accounting for the influence of the geometry, the regime and the stochasticity on the light-round is prohibitive due to the high costs of carrying out several experiments or simulations in different geometries. In the case of LES, even if spark models are starting to account for the stochasticity intrinsic to turbulent flames in single-burner geometries (Marrero-Santiago et al. 2020; Collin-Bastiani et al. 2019; Tang et al. 2018, 2021), several simulations of light-round in full scale geometries would still be necessary, thus still imposing a very high computational cost (Hassanalay et al. 2021).

One of the possible approaches to achieve low-cost parametric studies of the light-round is to employ a low-order tool. This way 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 a good accuracy with such a low-order model. SPINTHIR (Stochastic Particle INTEGRator for HIgh altitude Relight), employing a Lagrangian stochastic approach to evaluate ignition (Neophytou et al. 2012), is one of these low-order models. It mimics the flame propagation through Lagrangian flame particles, which are convected over the flow using a simplified Langevin model (Pope 2000) (relying on a time-averaged CFD solution of the non-reacting flow field) and propagate or quench depending on the local flow conditions. The SPINTHIR model performs a statistical evaluation of ignition by enabling various low cost simulations of the ignition transient. It has been validated and applied to both premixed, non-premixed, and spray flames (Neophytou et al. 2012; Sitte et al. 2016; Palanti et al. 2021)
producing very accurate results. In a recent work by Ciardiello et al. (2022), SPINTHIR was for the first time applied to reproduce the light-round process in an annular combustor close to its stability limits operating under premixed conditions. The authors showed that SPINTHIR is able to successfully simulate the light-round process in a broad range of flame speeds. However, the authors also showed that SPINTHIR largely over-predicted the light-round time. Furthermore, SPINTHIR did not fully 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 is, thus, 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. This study is carried out on a lab-scale annular combustor with premixed bluff-body stabilised flames (Ciardiello et al. 2020) (each individual burner having a geometry similar to the one used in Neophytou et al. (2012)) and the results of the simulations will be compared with data coming from experiments. Several cases are analysed, where flame speed and fuel are varied and light-round times are compared to experimental results. The paper is structured as follows: first the SPINTHIR model is introduced along with the proposed modifications. Then, the burner, the studied cases and the non-reacting CFD are described. Finally, results are presented and discussed.

## 2 Methods

### 2.1 The SPINTHIR Model and Proposed Modifications

#### 2.1.1 The Baseline SPINTHIR Model

The low-order model SPINTHIR (Neophytou et al. 2012) uses a time-averaged non-reacting CFD flow field to model the flame motion through Lagrangian flame particles. First, the numerical domain must be discretised in a regular hexahedral mesh, thus simplifying particle tracking. Each cell has four different states: (i) cold, (ii) burning, (iii) quenched and (iv) out of domain. All cells inside the domain are initiated as cold, while the ones outside the limits of the annular chamber are set to out of domain. Where the spark is defined, the cells that overlap the spark volume are assigned the burning state, each one releasing a flame particle and starting the simulation. The flame particles are then convected over the flow field, following a random walk based on a Langevin model (Pope 2000) described by the following equations:

\[ dX_{p,i} = U_{p,i} \, dt \]  \hspace{1cm} (1)

\[ dU_{p,i} = - \left( \frac{1}{2} + \frac{3}{4} C_0 \right) \omega_i (U_{p,i} - \bar{U}_i) \, dt + (C_0 \epsilon_i \, dt)^{1/2} N_{p,i} \]  \hspace{1cm} (2)

where \( dX_{p,i} \) is the particle displacement in the time interval \( dt \), \( \bar{U}_i \) 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. Equation 2 is composed of a first term corresponding to a linear drift from the mean velocity and of an isotropic
diffusion term. The random variable is different for each direction of movement for each particle, thus simply transporting them by the turbulent flow as a random walk.

As the flame particles are convected through the domain, their propagation is evaluated each time they move between mesh cells according to an extinction criterion based on a local Karlovitz number \( (Ka) \). A local Karlovitz number is calculated for each particle at each time instant using the definition based on the correlation proposed by Abdel-Gayed and Bradley (1985):

\[
Ka_p = 0.157 \left( \frac{\nu (\mu')^3}{L_{turb,i}} \right)^{1/2} \frac{1}{S_{L,i}^{2}}
\]  

where \( \nu \) is the kinematic viscosity of the mixture, \( \mu' \) is the rms velocity, \( L_{turb,i} \) is the turbulence length scale and \( S_{L,i} \) is the flame laminar speed. If a flame particle propagates inside a cold cell and this flame particle has a \( Ka_p \) number smaller than a critical Karlovitz reference value of \( Ka_{cr} = 1.5 \) (as defined by Abdel-Gayed and Bradley (1985) for premixed flames), the state of the cell is changed to burning, and a new particle is released, being added to the pool of flame particles that are propagating. Otherwise, the flame particle is extinguished. Additionally, because here we intend SPINTHIR to model the self-propagating premixed flame, if a particle moves back to a cell that was already burning, the particle is also quenched to mimic a movement towards burnt gases, where fuel is no longer available.

Each time step, a parameter called “ignition progress factor”, \( \Pi \), is calculated as the ratio between the number of ignited cells and the total number of cells. This parameter indicates the portion of the chamber that is visited by flame particles during the ignition transient and can hence be used to assess the behaviour of the combustor. Once all particles have quenched or all of the domain has been checked, the ignition progress factor is evaluated and the run is classified as a successful ignition or as a failure. Multiple simulations are performed in this way to evaluate the flame propagation and ignition probability.

### 2.1.2 The Turbulent Flame Speed Mismatch and Proposed Modifications

Ciardiello et al. (2022) 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 did not scale with the laminar flame speed as found in the experiments, as a consequence of the fact that the laminar flame speed is not a parameter in the model. Indeed, the baseline modelling for SPINTHIR relies on the Peters (1988) 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 modelling 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 (Kuo and Acharya 2012). This work proposes two modifications to address these limitations.

First, Flame-Generated Turbulent Intensity (FGTI) will be considered. This intends to consider effects of higher turbulent kinetic energy due to combustion (e.g. turbulence to flame interaction), which has been shown in the literature to considerably impact the flame front propagation in confined geometries (Vermorel et al. 2017; Quillatre et al. 2013; Kuo and Acharya 2012). Kuo and Acharya (2012) defined FGTI as the turbulent intensity being caused by the velocity jump on the flame front:

\[ \text{FGTI} = \frac{u'_{rms}}{S_L} \]
where $\overline{u'^2}, \overline{v'^2}$ and $\overline{w'^2}$ 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 for each case that will be then added to the non-reacting turbulent kinetic energy calculated by the CFD for each mesh cell. Turbulent intensity is then converted into the root mean square velocity fluctuation. This will then impact the flame particle movement in Eq. 2 through the $\omega_i$ term, the Karlovitz criterion (Eq. 3) and any flame speed expression explicitly considering $u'$.

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 in two ways:

**Model 1 - Turbulent Flame Speed Imposed to Flame Particles Every Time Step:** By modifying the magnitude of the flame particle velocity vector (but keeping its direction) issued from the Langevin equation. The velocity vector is normalised and then multiplied by a turbulent flame speed expression found in the literature ($S_T$):

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

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.

**Model 2 - Turbulent Flame Speed Imposed Only to Flame Particles’ Initial Velocity:** As the previous approach relies on overriding the Langevin model for the displacement of particles, we evaluate a second way to account for the turbulent flame speed, as modifying the turbulent motion modelling is not ideal. We propose then a second way of accounting for the turbulent flame speed in the flame particle movement, where we impose it as the initial velocity of the flame particles. At the moment of creation of a flame particle, the velocity vector of the mean flow (at the cell where the particle is being created) $\bar{U}_i$ will be normalised and then multiplied by the turbulent flame speed expression:

$$U_{p,i} = \frac{\bar{U}_i}{\sqrt{\bar{U}_1^2 + \bar{U}_2^2 + \bar{U}_3^2}} \times S_T$$

The particle is then normally convected by the Langevin model (Eqs. 1 and 2), as in the baseline SPINTHIR.

**Turbulent Flame Speed Modelling:** To implement these two modifications, various expressions for the turbulent flame speed from the literature and listed in Table 2 are evaluated. In addition, the expression retrieved by Ciardiello et al. (2020) by correlating the laminar flame speed with the flame front propagation speed based on fitting to the experimental data is also employed.
As this expression comes directly from the experimental results that are here evaluated, it is used as a means of validation of the modelling framework expressed by Eq. 5, as it should give sensible results by construction. Additionally, the use of this expression will help understand if imposing a velocity derived from the experimental flame front propagation on the individual motion of the flame particles is able to retrieve the same macroscopic flame front propagation in the SPINTHIR model.

2.2 Studied Case and Model Inputs

The calculations were performed for the Cambridge annular combustor, a premixed, swirled, bluff body stabilised annular combustor (see Refs. Ciardiello et al. (2020), Ciardiello et al. (2020), Ciardiello et al. (2020) for all details). It is composed of 18 swirl burners with bluff bodies. Figure 1 presents a drawing with the main dimensions of the burner. The individual burners comprise a cylindrical pipe (150 mm long, with an inner diameter of \( D_b = 18.9 \) mm), a swirler generating an anti-clockwise tangential flow (exit vane angle \( \alpha = 60^\circ \), geometrical swirl number \( S_g = 1.22 \) Worth and Dawson (2013)) and a conical bluff body (diameter of \( D = 13 \) mm and half angle of \( 45^\circ \), resulting in a blockage ratio of \( \sim 47\% \) at the burner’s exit). Two concentric cylindrical walls delimit the annular chamber having diameters of \( D_{inner} = 127 \) mm and \( D_{outer} = 203 \) mm, respectively, for the inner and outer walls.

In this study, the capability 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 Ciardiello et al. (2020), Ciardiello et al. (2020): the laminar flame speed

\[
S_T = \frac{\rho_u}{\rho_b} (3.82S_L + 1.33)
\]

(a) (b)

Fig. 1 a Schematic of the longitudinal section of the combustion chamber (flow from left to right). b Detail of one swirl bluff body burner (flow from bottom to top)
and the fuel type, modifying the unburnt-burnt gases density ratio. Table 1 summarizes the analyzed cases. The fuels employed are methane and ethylene.

The SPINTHIR grid size is chosen as $\Delta x = 3$ mm after a mesh convergence study to balance computational cost and good discretisation. The choice of the time step ($\Delta t$) should be done to prevent any flame particle from travelling more than $\Delta X$ each iteration, as particles jumping cells in the SPINTHIR model cause a bad estimation of the particle trajectory and of the ignition progress factor. This means defining $\Delta t$ in a way that in all cells the local CFL number should be always smaller than one. Therefore, after a convergence study on the light-round time, the time step is chosen as $\Delta t = 0.01$ ms to achieve this condition.

The size of the spark was chosen as a cube (due to the hexahedral mesh) of edge length of 6 mm based on the experimental observations (Ciardiello et al. 2020). Therefore, as the model considers one particle per mesh cell, this results in 8 flame particles being released to initiate the simulation. The spark is placed at an axial distance of $x/D = 0.5$ to the bluff body, where $D$ is the bluff body diameter.

The methodology for light-round calculation is similar to Ciardiello et al. (2022), where the ignition progress factor is used to calculate the light-round time, as the evolution of $\Pi$ follows the progression of the flame front across the chamber. This process is analogous to the experimental one done in Ref. (Ciardiello et al. 2020), to provide comparable results. For the experiments, $\Pi = 0.01$ marks the beginning of the light-round phase, while $\Pi = 0.8$ represents, in most cases, the end of it. However, the measurement of light-round time depends on the comparison of simulation images with the OH$^*$ images from the experiments in the annular combustor (Ciardiello et al. 2020). This results in setting the threshold to identify light-round in SPINTHIR simulations to $\Pi = 0.75$, as part of the SPINTHIR cells are out of the combustion chamber domain, and the ignition factor is not exactly the same thing as the OH$^*$ luminosity.

For each case tested, ten events are simulated, with the light-round time taken as the average value between them. This resulted in 550 simulations in total for this study.

### 2.3 Non-Reacting CFD Input

The CFD flow fields needed for the SPINTHIR calculations were obtained using the Rolls-Royce plc. proprietary finite volume code PRECISE-UNS (Anand et al. 2014). 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 $\dot{m} = 2.59 \text{ g/s}$ is specified, resulting in the $u_{\text{bulk}} = 16 \text{ m/s}$ at the chamber entrance. Since the case is fully premixed, the equivalence ratio is then set to the desired value inside the whole chamber

| Fuel | # burners | $U_{\text{mix}}$ | $\phi$ | $S_L$ (cm/s) | Spark location $[x/D]$ |
|------|-----------|-----------------|--------|-------------|----------------------|
| CH$_4$ | 18 | 16 | 0.75-0.85-1 | 24-30-36 | 0.5 |
| C$_2$H$_4$ | 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 |
before running the SPINTHIR simulations. A large cylindrical region is added at the exit of the chamber to mimic the atmosphere. The pressure and temperature are 1 atm and 293 K respectively and the walls are considered adiabatic, as thermal exchanges with the walls are not included here.

Figure 2 displays cut planes of the annular chamber, showing the axial component of the velocity field and the pseudo-stream lines from a burner. At the exit of a single burner the mixture axial velocity is close to 16 m/s, as expected from the imposed mass flow rate. As shown in Fig. 2a, the presence of a bluff body and a swirler and the interaction between adjacent flows resulted in the formation of two recirculation zones: (i) a Central Recirculation Zone (CRZ), in the wake of the bluff body and (ii) a Side Recirculation Zone (SRZ) in the inter-burner region. The CRZ extended for \( \sim 1.5 D \) and the axial velocity was \( \sim -5 \) m/s (see Fig. 2c), while the SRZ was shorter (\( \sim D \) tall) and characterised by a negative axial velocity of \( \sim -3 \) m/s. The swirler added upstream of the bluff body generated an anticlockwise tangential flow. Figure 2c and d present two cross-sectional cuts showing the axial velocity at the two positions where the kernel will be initiated. One can see that the kernel being initiated at \( x/D = 0.5 \) (Fig. 2c) means it is inside the CRZ. The tangential component of the velocity ranges in magnitude between \( \sim -13 \) m/s and \( \sim 13 \) m/s, both in the CRZ and in the SRZ. Finally, Fig. 2b shows the flow pseudo-streamlines as initiated at the initial position of the ignition kernel. Some possible paths for the particles (as carried by the mean flow) are highlighted, showing how the mean flow connects different burners by the SRZs and CRZs, moving the flame particles from burner to burner, promoting the light-round.

3 Results and Discussion

3.1 Model 1: Turbulent Flame Speed Imposed to Flame Particles Every Time Step

3.1.1 Evaluation of Turbulent Flame Speed Expressions

On the first set of calculations, all the expressions in Table 2 were used, 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 \( S_L = 24 \) 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 Table 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 turbulence modification by 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 (Ciardiello et al. 2020): this 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
Fig. 2 RANS simulations: a Bluff-body mid-plane cut showing the axial velocity field, with the Central Recirculation Zone (CRZ) and Side Recirculation Zone (SRZ) in shades of blue. b Pseudo streamlines showing some of the possible paths from particles initialised at the centre of a bluff-body. The arrows highlight paths where the particles can move to ignite the mixture in the neighbouring injectors by the SRZs and the CRZs. c and d Cross-section cuts at $x/D = 0.5$ and $x/D = 5$, respectively, showing the axial velocity fields at the positions where the kernels are initiated. Please contact authors if a scheme adapted to colour-blindness is needed.
the turbulent flame speed, one can see that only four are close to the experimental one: Clavin and Williams (1979), Bray (1990) and the two expressions from Ishizuka et al. (1998). 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.

### 3.1.2 Effect of Laminar Flame Speed Variation

The three laminar flame speed cases for methane are summarised in Fig. 3a. First analysing the baseline SPINTHIR, one can see that the result found by Ciardiello et al. (2022) is here retrieved: the baseline model cannot capture the effect of laminar flame speed over the light-round time. When FGTI is introduced to the baseline model, the flame particles propagation starts to be influenced by the laminar flame speed and, as the flame speed

| Reference                  | Equation                                                                 | Light-round time [ms] |
|----------------------------|--------------------------------------------------------------------------|-----------------------|
| Experiments                |                                                                          | 18.0                  |
| Baseline                   |                                                                          | 55.27                 |
| Baseline with FGTI         |                                                                          | 51.02                 |
| Ciardiello et al. (2020)   | \( S_T = \frac{\rho_u}{\rho_b} (3.82S_L + 1.33) \)                      | 18.21                 |
| Damkohler (1940)           | \( \frac{S_T}{S_L} \approx \frac{1}{Re_{L}}^{1/2} \)                    | 31.26                 |
| Abdel-Gayed and Bradley (1977) | \( \frac{S_T}{S_L} \approx \frac{1}{Re_{L}}^{0.24} \)                | > 80                  |
| Libby et al. (1979)        | \( \frac{S_T}{S_L} = 2.1 \left( \frac{u'_{rms}}{S_L} \right) \)         | 65.11                 |
| Clavin and Williams (1979) | \( \frac{S_T}{S_L} = 1 + \left( \frac{u'_{rms}}{S_L} \right)^2 \)        | 17.23                 |
| Liu and Lenze (1989)       | \( \frac{S_T}{S_L} = 1 + 5.3 \left( \frac{u'_{rms}}{S_L} \right)^{3/5} \) | 51.90                 |
| Bray (1990)                | \( \frac{S_T}{S_L} = 7.25 \left( \frac{u'_{rms}}{S_L} \right)^{4/3} \)  | 16.79                 |
| Kerstein and Ashurst (1994) | \( \frac{S_T}{S_L} = 1 + \left( \frac{u'_{rms}}{S_L} \right)^{4/3} \)  | 67.84                 |
| Ishisuka et al. (axial) Ishizuka et al. (1998) | \( S_T = \left( \frac{\rho_u}{\rho_b} S_L^2 + u'_{\max} \right)^{1/2} \) | 15.74                 |
| Ishisuka et al. (radial) Ishizuka et al. (1998) | \( S_T = S_L + u'_{\max} \left( 1 + \frac{\rho_u}{\rho_b} \right)^{0.5} \) | 17.33                 |
increases, the light-round time reduces. However, despite introducing the correct trend, the baseline SPINTHIR with FGTI still overestimates the light-round time in all cases. When Ciardiello’s turbulent flame speed expression is applied, the model gives excellent predictions, confirming that this framework is also capable of capturing the laminar flame speed effect. Regarding the expressions coming from the literature, multiple results are observed. Clavin and Williams (1979) expression presents a laminar flame speed trend opposite to the one observed during the experiments. Indeed, looking at Clavin and Williams (1979) equation, the turbulent flame speed is inversely proportional to the laminar flame speed. Both Ishizuka et al. (1998) 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 modelling (Bray 1990) produced an excellent agreement with the experimental results for the three laminar flames. It must be noted that the Bray model does not consider the laminar flame speed explicitly in its formulation of the turbulent flame speed, similarly to the baseline SPINTHIR model (relying on the Peter’s (Peters 1988) assumption). In both cases the effect of the laminar flame speed on the flame particles’ movement is accounted only through FGTI, which is then translated through the increased $u'_{xy}$ term in their turbulent flame speed expressions. In the Bray and Peter’s models it is only through FGTI that the laminar flame speed can affect the light-round time, showing the relevance of modelling FGTI for these two approaches. Indeed, this is further confirmed by the Bray’s expression coupled with FGTI reproducing well not only the light-round time, but also the good scaling of it with the variation of laminar flame speed (Fig. 3).

The results for ethylene, shown in Fig. 3b, confirm the previously discussed for methane. As the Bray (1990) and Ciardiello et al. (2020) 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 (Bray 1990) 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 (Ciardiello et al. 2020). 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 a 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 min per simulation in a single core of a local workstation).

3.2 Model 2: Turbulent Flame Speed Imposed Only to Flame Particles’ Initial Velocity

In the last section we saw that using the correlation for the turbulent flame speed from the Bray (1990) model resulted in a good agreement with experiment. However, as the ”Model 1” approach relied on overriding the Langevin model for the displacement of particles, this is not completely satisfactory. Even if that choice of modelling resulted in a good reproduction of the experimental light-round time with no a priori information, it reduced the stochasticity of particles movement and the flame front propagation was different to the experiments, as it will be shown later. Furthermore, in the context of the SPINTHIR model, it is important to understand separately the impact of the initial velocity attributed to the flame particles and the effect of their convection on the resulting light-round time. Therefore, in this section we further explore this problem now using the Model 2 (Sect. 2.1), where the turbulent flame speed is imposed only as the initial velocity of the flame particles. However, for these simulations, not all expressions will be used, with only the Bray (1990) expression being reused (and being compared with the previous modelling). An additional expression is also considered, after observing that for the first model the Bray expression does not manage to follow the speed up seen in the experiments for the higher density ratios and laminar flame speed velocities. Thus, we introduce the density ratio in a more explicit form into the turbulent flame speed expression, which would be equivalent to multiply the density ratio to the Peter’s model:

\[
S_T = \frac{\rho_u}{\rho_b} u'_{rms}
\]  

(8)

and, as the Bray model in this section, it will be used only to initialise the flame particles’ velocity, as shown in Eq. 6 with FGTI still considered.

Figure 4 presents the results for this new set of tests. First, comparing the initial results for the Bray model (cyan dots) with the new ones where the Bray expression is imposed as the initial velocity of the particles (purple dots), one can see that imposing the turbulent flame speed only to the initial velocity of the particles did not change much the light-round time. However, two benefits where achieved, as in this new approach the mean velocity of the field is explicitly accounted in the initialisation of the flame particles velocity:

- the flame front propagation became much closer to the experiments, with an asymmetric propagation (Figs. 5 and 7). This happens as the bottom front travels faster than the top one, because it is travelling in the same direction of the swirl movement. However, for the original Bray model implementation, both fronts travels at the same speed and the flame front propagation is always symmetric. This is corrected when the turbulent...
The flame speed expression is applied only to the initial instant and taking into account the mean flow velocity when creating the flame particles (following Eq. 6).

- Accounting for the mean flow in the initial particles velocity produces a marginal speed up of the process, making the results closer to the experiments for the higher laminar flame speed cases.

Therefore, this shows that only imposing the turbulent flame speed expression to the initial velocity of the particles is the best strategy, as it produces results closer to the experiments and has the additional benefit of respecting the physics of the Langevin equation and random walk process of the fluid particle movement.

Finally, looking at the light-round time results when the density ratio is explicitly considered alongside Peter’s expression (Eq. 8) in Fig. 4 (green dots), one can see that it further improved the results. Indeed, considering the density ratio in the turbulent flame speed managed to increase the light-round time resulting from the SPINTHIR simulations for the smaller density ratio and laminar flame speed cases. This can be seen in Fig. 5, where the flame propagation for the C2H4 and $S_L = 24$ cm/s is presented. While the Bray models over estimate the flame front propagation speed, the $S_T = \frac{\rho_a u'_r}{\rho_b u'_r}$ case has a propagation very similar to the experiments, finishing the light-round very closely to the experiments. Additionally, this latter strategy also captures the asymmetry of the flame front propagation, showing that this feature is retained while we impose the turbulent flame speed to the initial velocity of the flame particles (Eq. 5), independently to which turbulent flame speed expression is used. Observing the side view of the flame front propagation (Fig. 6), one can see how this initial velocity strategy also increases the stochasticity of the vertical propagation, as the flame front is less uniform when compared to the original Bray case (cyan images).

When looking at the $S_L = 59$ cm/s case, one can see that the $S_T = \frac{\rho_a u'_r}{\rho_b u'_r}$ expression reduced the light-round time for the higher density ratio and laminar flame speed cases, providing better results where the Bray model failed to reproduce the speed up of the flame front with laminar flame speed and density ratio. Fig. 7 shows how the
$S_T = \frac{\rho_u u'_t}{\rho_b u'_{rms}}$ expression produces a flame front propagation faster than the other cases, almost matching the experimental results. It must be noted, however, that propagation speed of the flame front in the experiments is not constant, as shown by Fig. 7. In the first two instants, the experimental flame front will travel faster than the $S_T = \frac{\rho_u u'_t}{\rho_b u'_{rms}}$ case, while in the last two it is progressively matched by the $S_T = \frac{\rho_u u'_t}{\rho_b u'_{rms}}$ case. This likely happens as in reality the flame front is slowed down in the final moments by the resistance of fresh gases as they are compressed by the travelling flame front and becomes more evident for the high density ratio cases (as the the $S_L = 59 \text{ cm/s}$ one). Additionally, heat transfer at the combustor walls is also neglected, which has been shown recently in the literature to impact light-round in liquid-fuelled combustors (Töpperwien et al. 2022; Puggelli et al. 2019). These effects are not considered in the SPINTHIR model, where each side of the flame front propagates with an almost constant velocity. Even if the SPINTHIR model is only able to represent an average

Fig. 5 Top view of the evolution of the flame front during light-round for C2H4, $S_L = 24 \text{ cm/s}$ for (from top to bottom) experiments (OH* images), Bray expression (cyan particles), Bray expression only to initial velocity (purple particles) and density ratio time $u'_{rms}$ case (green particles)
behaviour for the flame front propagation, it captures very well how each side propagates and the final light-round time (as shown in Fig. 7). Looking at the side view of the same case (Fig. 8), one can see that in the experiments the flame front initially propagates faster azimuthally \((t = 2.5 \text{ ms})\), while in the SPINTHIR model, the vertical propagation is initially faster. However, the experimental flame front later accelerates and in all cases, except the original Bray one, the flame reaches the end limits of the chamber roughly at the same time.

Therefore, these final results and comparisons with the experiments show that: (1) the best strategy to introduce the turbulent flame speed expression is to impose it only to the initial velocity of the flame particles; and (2) that the expression 
\[
S_T = \frac{\rho_u}{\rho_b} u'_{\text{rms}},
\]
where the density ratio is applied along with the Peter’s assumption (Peters 1988), considered along with FGTI, resulted in the best agreement with the experiments. Indeed, in this manner the light-round time is very well predicted with no a priori experimental knowledge and with an average error of 8%, even better than the results achieved by the Bray model.

Fig. 6 Side view of the evolution of the flame front during light-round for C2H4, \(S_L = 24 \text{ cm/s}\) for (from top to bottom) experiments (OH* images), Bray expression (cyan particles), Bray expression only to initial velocity (purple particles) and density ratio time \(u'_{\text{rms}}\) case (green particles)
4 Conclusions

The low-order model SPINTHIR was applied to an annular premixed combustor to predict light-round time. It was found in previous studies (Ciardiello et al. 2022) 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 et al. (2020) was also used to test the framework against the experimental data.

The modified SPINTHIR model using Ciardiello’s 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 (Bray 1990) 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 (1990) emphasises the important of modelling FGTI, as Bray’s expression relies only on the scaling of flow $u'_{\text{rms}}$ with the laminar flame speed.

Analysing these successful results, some further improvements were suggested. First, we observed that the turbulent flame speed only needed to be imposed to the initial velocity of the particles. This change made the flame front propagate very closely to the experiments in an asymmetrical manner with the bottom front faster than the top one, in a clear improvement. Second, we considered another turbulent flame speed expression, this time explicitly accounting for the density ratio with the Peter’s assumption (Peters 1988), leading to $S_T = \frac{\rho_u}{\rho_b} u'_{\text{rms}}$. This expression, coupled with the FGTI model, is also

Fig. 8 Side view of the evolution of the flame front during light-round for C2H4, $S_L = 59$ cm/s for (from top to bottom) experiments (OH$^*$ images), Bray expression (cyan particles), Bray expression only to initial velocity (purple particles) and density ratio time $u'_{\text{rms}}$ case (green particles)
only used to impose the initial velocity of the particles. This final modelling leads to an excellent agreement with the experiments, producing the best results in terms of reproducing the flame front propagation and the light-round time of the experiments. With an average error of 8% (maximum error of 23% and minimum error of 1%), this setup produces the best results for all cases studied. Therefore, this work shows that it is possible to have a good estimation of light-round time in premixed combustors with a low order model with very low computational cost, as each simulation would take on average 75 min to run in a single core of a local workstation. We aim then in testing the model in a setting closer to realistic combustors (i.e. partially premixed liquid-filled with heat transfer at the walls) to move forward in the development of SPINTHIR towards industrial applications.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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