frontiers in Mechanical Engineering

MINI REVIEW
published: 16 November 2020
doi: 10.3389/fmech.2020.512501

A Review of the Numerical Investigations of Jet-In-Hot-Coflow Burner With Reactor-Based Models

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Moderate or Intense Low-oxygen Dilution (MILD) combustion is considered as one of the most promising novel combustion technologies, as it ensures high efficiency and very low emissions (NO_x and CO). Because of the high level of dilution, the system reactivity is reduced and the chemical time scale is increased compared to conventional flames. Therefore, combustion models accounting for finite-rate chemistry are needed to study the characteristics of such flames. Reactor based models, such as the Partially Stirred Reactor and the Eddy Dissipation Concept models have been successfully used to model MILD combustion. This article describes recent progress and developments in the application of reactor based models for the simulation of the jet-in-hot-coflow burners that emulate MILD combustion. The main objective is to provide an overview about the current state of the art of reactor based models for turbulence-chemistry interactions in MILD regime and outline future prospects for the further development of such models. The literature acknowledges both Reynolds Averaged Navier Stokes and Large Eddy Simulations studies, with various operating conditions as well as different fuels. The results indicate that it is necessary to include both the mixing and chemical time scales explicitly in the combustion model formulation. Because of the distributed reaction area, according to recent investigations, Large Eddy Simulation grid can be sufficient to resolve the MILD combustion reacting structures. The present review underlines the importance of finite rate chemistry in MILD combustion simulations, as well as of providing reliable estimation of the characteristic time scales.

Keywords: jet-in-hot-coflow burner, reactor-based models, MILD combustion, turbulence-chemistry interaction, finite rate chemistry

OPEN ACCESS

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Specialty section:
This article was submitted to Thermal and Mass Transport, a section of the journal Frontiers in Mechanical Engineering

Received: *15 November 2019*
Accepted: *05 October 2020*
Published: *16 November 2020*

Citation:
Li Z and Parente A (2020) A Review of the Numerical Investigations of Jet-In-Hot-Coflow Burner With Reactor-Based Models. Front. Mech. Eng. 6:512501. doi: 10.3389/fmech.2020.512501

INTRODUCTION

Facing the current challenges of air pollution and energy shortage, it is urgent to develop fuel flexible, efficient and environmentally friendly combustion technologies. Novel combustion technologies with low emissions, high efficiency and fuel flexibility have become essential under these challenges (Li, 2019). In this context, one promising technology in energy production and manufacturing is Moderate or Intense Low oxygen Dilution (MILD) combustion (Wünning and Wünning, 1997; Cavaliere and de Joannon, 2004; de Joannon et al., 2012).

MILD combustion is established by diluting the fresh reactants with the combustion products and preheating the charge above the self-ignition temperature of the fuel (de Joannon et al., 2012). The

high dilution is responsible for the widening of the reaction zone, while the mixing with hot exhaust gases ensures that reaction takes place also outside of the flammability limits. In terms of characteristic scales, the dilution lowers the oxygen concentration and smooths the temperature peaks. As a result, the chemical time scale increases and the strong interaction between chemistry reaction and mixing makes the investigation of such flames more challenging than conventional combustion regimes. The availability of validation data is then crucial to advance the current understanding of MILD combustion and further push its implementation in industrial applications. To decrease the influence of geometric complexity encountered in practical devices, simplified lab-scale axis-symmetric jet burners are generally used to emulate MILD conditions—for example, the jet-in-hot-coflow (JHC) burner (Dally et al., 2002; Oldenhof et al., 2010).

The JHC burner features a central jet and a secondary burner providing hot exhaust products as a coflow, reproducing the flue gas recirculation. The oxygen level in the coflow is highly diluted by adding nitrogen and it is generally controlled below 10% by mass or volume (Dally et al., 2002; Medwell et al., 2007; Oldenhof et al., 2010; Medwell and Dally, 2012; Ye et al., 2015a; Ye et al., 2017). The literature acknowledges a large number of studies on JHC burners, both experimental and numerical (Dally et al., 2002; Oldenhof et al., 2010; De et al., 2011; Medwell and Dally, 2012; Evans et al., 2015; Parente et al., 2015; Li et al., 2017). Both gaseous (Dally et al., 2002; Medwell et al., 2007; Oldenhof et al., 2010; Medwell and Dally, 2012; Mardani and Karimi Motaalegh Mahalegi, 2019), simple hydrocarbon fuels and liquid (Ye et al., 2015a; Ma et al., 2016; Ye et al., 2017;Ye et al., 2018; Mahalegi and Mardani, 2019), oxygenated or long-chain alkane fuels have been used as fuel. The liquid, long-chain alkane fuels show different characteristics (Ye et al., 2015a; Ye et al., 2017) under MILD conditions, compared to gaseous fuels.

Numerical investigations on the JHC burners were carried out mainly using Reynolds Averaged Navier-Stokes (RANS) (Christo and Dally, 2005; Frassoldati et al., 2009; Mardani et al., 2010; Shabanian et al., 2012; Parente et al., 2015; Evans et al., 2015; Aminian et al., 2016; Mardani, 2017; Evans et al., 2017; Chen et al., 2017; Li et al., 2017; Li et al., 2018b) simulation and Large Eddy Simulation (LES) (Afarin et al., 2011; Ihme and See, 2011; Ihme et al., 2012; Li et al., 2019). LES can capture more faithfully the flow features while RANS is still important for preliminary investigations, because of its reduced computational cost. However, despite high computational efficiency of RANS simulation, non-equilibrium phenomena are not well captured by steady-state assumptions. To this end, Large Eddy Simulation (LES) can provide superior results with respect to RANS.

Due to the presence of the coflow and the intense low-oxygen dilution, combustion in JHC burner is characterised by a relatively low Damköhler number ($Da = \tau_m/\tau_c$, *the ratio of the mixing to chemical time scale*). The interactions between the chemical reaction and fluid dynamics has therefore become more important. Finite-rate chemistry models with detailed chemical mechanisms are necessary. On one hand, combustion models for conventional flames usually rely on the assumption of time-scale separation (i.e., steady flamelets and related models). These models are computationally efficient, while the thermo-chemical space accessible in the numerical simulations is constrained. Furthermore, huge effort could be spent on the pre-processing steps, especially when dilution level in MILD regime and heat losses are considered (Lamouroux et al., 2014; Locci et al., 2014). On the other hand, the use of transported PDF methods (Haworth and Pope, 2010) appears still computationally prohibitive, especially for practical combustion systems. Reactor based models, including the Partially Stirred Reactor (PaSR) (Chomiak, 1990; Golovitchev and Chomiak, 2001) approach and the Eddy Dissipation Concept (EDC) (Magnussen, 1981; Gran and Magnussen, 1996; Magnussen, 2005) model, have been extensively used in the past years because of their affordable treatment of detailed chemistry, showing promise for modelling MILD combustion.

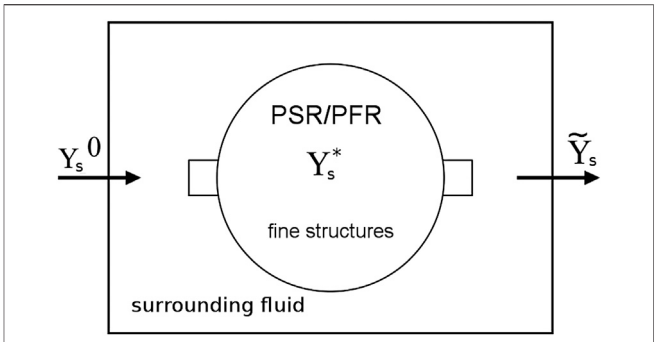

Figure 1 | Conceptual drawing of the reactor based models.

REACTOR BASED MODELS

Both the Partially Stirred Reactor (PaSR) approach and the Eddy Dissipation Concept (EDC) model are based on the assumption that each computational cell can be separated into two zones. Th reacting zone is generally referred to as "fine structures" (Magnussen, 1981; Chomiak, 1990; Gran and Magnussen, 1996; Golovitchev and Chomiak, 2001; Magnussen, 2005) while the non-reacting one is the "surrounding fluid". Combustion takes place in the fine structures in contact with a surrounding fluid. The average reaction rate in a cell is then the results of an exchange between the fine structure and surrounding fluid. The fine structures are modelled as Perfectly Stirred Reactors (PSR) or Plug Flow Reactors (PFR). A conceptual drawing of the PaSR and EDC model is presented in **Figure 1**.

Eddy Dissipation Concept Model

The EDC model is based on a cascade model (Gran and Magnussen, 1996) providing the mass fraction of the fine structures, γ_λ, and the mean residence time of the fluid within the fine structures τ^*, as a function of the flow characteristic scales:

$$\gamma_\lambda = C_\gamma \left(\frac{\nu\tilde{\epsilon}}{\tilde{k}^2}\right)^{\frac{1}{4}}, \quad (1)$$

$$\tau^* = C_\tau \left(\frac{\nu}{\tilde{\epsilon}}\right)^{\frac{1}{2}}. \quad (2)$$

In **Eq. 1** and **Eq. 2**, ν is the kinematic viscosity, $C_\gamma = 2.1377$ and $C_\tau = 0.4083$ are model constants (Gran and Magnussen, 1996). The mean reaction rate (source term in the species transport equation) is expressed as (Gran and Magnussen, 1996):

$$\overline{\dot{\omega}}_s = -\frac{\bar{\rho}\gamma_\lambda^M \chi}{\tau^*\left(1-\gamma_\lambda^N \chi\right)}\left(\tilde{Y}_s - Y_s^*\right). \quad (3)$$

The term $\tilde{Y}_s$ in **Eq. 3** denotes the mean mass fraction of the species *s* between the fine structures and the surrounding fluid and Y_s^* is the mass fraction of species *s* in the fine structures. The reacting fraction of fine structures is denoted with χ and it is often set to unity (Lewandowski and Ertesvåg, 2018; Lewandowski et al., 2020b). In **Eq 3**, M = 2 and N = 3. In the other two version of the EDC model (Magnussen, 1981, 2005), the combinations M = 3/N = 3 and M = 2/N = 2 have been used.

Partially Stirred Reactor Model

In the PaSR model (Chomiak, 1990; Golovitchev and Chomiak, 2001), the parameter κ is used to represent the mass fraction of the reaction zone (fine structures) in the computational cell. It can be estimated as (Chomiak, 1990; Golovitchev and Chomiak, 2001; Kärrholm, 2008):

$$\kappa = \frac{\tau_c}{\tau_c + \tau_{mix}}, \quad (4)$$

where τ_c and τ_{mix} are the characteristic chemical and mixing time scales in each cell, respectively. The mean source term provided to the species transport equation can be expressed as:

$$\overline{\dot{\omega}}_s = \kappa \frac{\tilde{\rho}\left(Y_s^* - \tilde{Y}_s\right)}{\tau^*}, \quad (5)$$

where τ^* represents the residence time in the reactive structure. In order to get Y_s^*, a system of ODE is solved for the reacting structures.

Finite-Rate Chemistry Effects

In both models, the mean mass fraction $\tilde{Y}_s$ is obtained by solving transport equations for the reactive scalars induced in the kinetic mechanism. The mass fraction of each species inside the fine structures Y_s^* is estimated assuming that the latter are Perfectly Stirred Reactors (PSR), which allows to use detailed chemical mechanisms (Gran and Magnussen, 1996):

$$\frac{\dot{\omega}_s^*}{\rho^*} = \frac{1}{\tau^*}\left(Y_s^* - Y_0\right), \quad (6)$$

where $\dot{\omega}_s^*$ is the formation rate of species s and Y_0 is the species mass fraction in the surrounding fluid (Gran and Magnussen, 1996). Alternatively, the fine structures can be modelled as Plug Flow Reactors (PFR), evolving over a characteristic time equal to τ^*:

$$\frac{Y_s^\star}{dt} = \frac{\dot{\omega}_s}{\rho}. \quad (7)$$

DISCUSSION

Successful predictions of JHC flames are reported in the literature. In the context of RANS simulation using EDC model, over-predictions of temperature were observed using standard EDC constants of $C_\gamma = 2.1377$ and $C_\tau = 0.4083$, as reported by different authors (De et al., 2011; Aminian et al., 2012; Shabanian et al., 2012; Evans et al., 2015; Li et al., 2017; Mardani, 2017; Li et al., 2018b). Aminian et al. (Aminian et al., 2012) performed RANS simulation on the JHC burner with CH_4/H_2 as fuel. In the experiments, the co-flow oxygen level was adjusted to 3%, 6% and 9% with the addition of N_2. The fuel jet Reynolds number was 10,000. They found out that the standard EDC over-predicts the peak temperature downstream of the burner (120 mm from the burner exit). They concluded that residence time in the fine structures should be increased, to decrease the average reaction rate. To this end, the value of C_τ was increased to 1.5 and 3.0. It was finally concluded that $C_\tau = 1.5$ was the best option for both co-flow oxygen levels, i.e., 3% and 9%.

De et al. (2011) studied Delft JHC with Dutch natural gas as a fuel, numerically. Under-prediction of the flame lift-off height was observed with the EDC model, while the flame temperature were generally over-estimated. The authors proposed to change not only the time scale constant C_τ, as done by Aminian et al. (2012), but also C_γ, to directly impact the mass fraction of reacting structures. Based on a sensitivity analysis, the authors finally selected $C_\tau = 3.0$ or $C_\gamma = 1.0$ (C_τ and C_γ are not changed at the same time).

The modified C_τ constant value used by De et al. was adopted by Shabanian et al., (2012), when simulating the JHC burner fed with ethylene. The modified k-ϵ model reported by Aminian et al. (2012) was used. They compared three different combustion models in their research work: the steady flamelet model, EDC and transported PDF. Results obtained with the adjusted EDC coefficients and transported PDF showed superior performances compared to the standard steady flamelet model. Christo et al. (Christo and Dally, 2005) also compared three combustion models: ξ/PDF, flamelet model and EDC model in RANS, leading to the conclusion that conserved-scalar based models like ξ/PDF and flamelet models are inadequate for the JHC configuration. Chitgarha et al. (Chitgarha and Mardani, 2018) investigated the potential of flamelet modelling for JHC flames with RANS as well. Results with lower accuracy than the EDC model are obtained, though lower computational cost is required by the flamelet model. Chen et al. explored the tabulation of a Perfectly Stirred Reactor (PSR) covering the entire flammability range to model the JHC case. Good agreement is observed except for the CO prediction Chen et al. (2017). Furthermore, Kim et al. (Kim et al., 2005) explored the application of conditional moment closure (CMC) model on the JHC configuration, showing attractive predictions.

Evans et al. (Evans et al., 2015) carried out a systematic study and found out that adjusting the EDC parameters to $C_\gamma = 1.0$ and $C_\tau = 3.0$ resulted in significantly improved predictions under different fuel compositions (C_2H_4, H_2, N_2). Later in 2016, Tu et al. (Tu et al., 2016) adopted $C_\gamma = 1.0$ and $C_\tau = 3.0$ to investigate the physical and chemical effects of CO_2 addition to CH_4/H_2 JHC Flames. The same was done by Li et al. (Li et al., 2018b), when evaluating the on the fly chemistry reduction and tabulation methods with detailed kinetic mechanisms. Additionally, the combination of $C_\gamma = 1.0$ and $C_\tau = 1.47$ was also tested, showing satisfactory predictions of the Dutch natural gas and biogas JHC flames.

The studies discussed above focused on the modification of C_τ or C_γ, based on available experimental data. Different from the previous authors, Mardani et al. (Mardani, 2017) proposed a modification of the energy cascade parameters C_{D1} and C_{D2}, eventually affecting the values of C_τ and C_γ. In their work, the constant C_{D2} was changed from 0.0239 to 27 while C_{D1} was kept to its original value of 0.134. By this variation, the C_τ and C_γ coefficients in EDC model were varied between 0.0893–3.0 and 1.0–5.795, respectively. By these changes, the model was able to capture the flame lift-off of the reaction zone location and features.

Several sensitivity analyses have been carried out on the JHC burner using EDC model (De et al., 2011; Aminian et al., 2012; Shabanian et al., 2012; Tu et al., 2016; Mardani, 2017; Li et al., 2018a; Li et al., 2018b), to investigate the effect of different modelling choices, focusing on turbulent and combustion model parameters, as well as on the fuel and co-flow compositions. A comprehensive sensitivity study of the JHC burner was carried out by Li et al. (2017), using RANS. Their investigation includes the effect of turbulent combustion model formulations, boundary conditions, differential diffusion, turbulence model parameters and kinetic mechanisms on the results. Results showed that the reactors chosen, namely as Perfectly Stirred Reactors (PSR) or Plug Flow Reactors (PFR), to model the reaction fine structures, do not have a major impact on the results. Moreover, increased kinetic mechanism complexity does not lead to major improvements on the numerical predictions, suggesting that low-temperature oxidation mechanism are not relevant to the fuels and conditions investigated. While the inclusion of differential (molecular) diffusion and the appropriate choice of turbulent non-dimensional values such as Schmidt and Prandtl numbers helped to improve the prediction accuracy. The effect of molecular diffusion was also investigated by Salavati-Zadeh et al. (2018) with the conclusion that the inclusion of the molecular diffusion with proper Schmidt numbers for each species improves the prediction accuracy. The importance of differential diffusion was recognized by Christo and Dally, (2005) and Mardani et al. (2010) as well. In the work of Li et al. (2017), three different Eddy Dissipation Concept (EDC) model formulations were compared as well, showing their interaction with the choice of the $C_{1\epsilon}$ constant in the $k-\epsilon$ turbulence model. Christo and Dally, (2005) also studied the interactions between combustion model and turbulence model under RANS framework, concluding that the variations of k-ϵ model like the renormalization group and the relizable k-ϵ models perform worse than the standard k-ϵ with the modified constant of $C_{\epsilon 1} = 1.6$.

All EDC modifications presented above were based on a fitting procedure aimed at alleviating the temperature over-estimation observed with the standard EDC formulation. Parente et al. (2015) proposed a modification of EDC based on the revision of the energy cascade, taking into account the microscopically distributed features of MILD combustion. In particular, it was assumed that the reacting structures propagated with a turbulent flame speed expressed using the Damköhler formulation for high-intensity turbulence. With this assumption, the energy cascade coefficients C_{D1} and C_{D2} could be expressed as a function of the local turbulent Reynolds and Damköhler number of the flow. The estimation of the chemical time scale required in the Damköhler number was first based on a global reaction mechanism, and later extended to detailed chemistry by Evans et al. (2019). Beside the model constants C_{D1} and C_{D2}, Lewandowski and Ertesvåg (2018) proposed a modification on the reacting fraction χ of fine structures, which is often set to unity in other studies. They observed better agreement with experimental measurement when the reacting fraction is reduced below unity, with an improvement of both temperature and lift-off height predictions.

With the exception of the EDC formulation proposed by Parente et al. (2015) and Evans et al. (2019), the mass fraction of the fine structures and the residence time are solely determined by flow properties in EDC. However, MILD combustion is driven by the strong overlap of fluid dynamic and chemical scales. This suggests that the characteristic chemical time scale shall be included in the definition of the reacting structure features. This has pushed the investigation of PaSR approach for modelling MILD combustion. As indicated in **Section 2.2**, both chemical time scale and mixing time scale are used for the determination of κ, which is the factor accounting for non-perfect mixing (turbulence-chemistry interaction). Li et al. (2017) compared the EDC model with standard model constants to the standard PaSR model, for the simulation of JHC burner with C_2H_4, H_2, H_2O as fuel. The prediction of mean temperate and species mass fraction (including H_2O and NO) improved significantly using PaSR, indicating its potential for MILD combustion. There are several ways to estimate the characteristic time scales required by the model (Li et al., 2018a; Ferrarotti et al., 2019). It was showed that appropriate choices of mixing and chemical time scales are crucial to ensure the prediction accuracy. Li and Ferrarotti et al. (Li et al., 2018a; Ferrarotti et al., 2019) reported that a dynamic evaluation for mixing time scale show superior performance for the configuration. The dynamic evaluation adopts mixing time scale as the ratio between the variance of mixture fraction and its dissipation rate, rather than global estimations based on Kolmogorov or integral mixing scales. Different approaches to evaluate chemical time scale were also compared, based on the species formation rates, the reaction rates and the eigenvalues of the formation rate Jacobian matrix (Li et al., 2018a). Various co-flow oxygen dilution levels and Reynolds numbers over a wide range of operating conditions (with C_2H_4, H_2, H_2O as fuel) were included in the validation work.

The JHC configuration was also investigated using LES, to improve the prediction of intermediate and minor species, as well as to capture the intermittency observed in some configurations when increasing the fuel jet Reynolds number (Parente et al., 2015). LES using a three-stream Flamelet Progress Variable

TABLE 1 | Comparison of combustion models

Models	Details	Findings	References
Standard EDC (RANS)	—	Over-predicted temperature at axial location = 120 mm	De et al. (2011); Aminian et al. (2012); Shabanian et al. (2012); Evans et al. (2015); Li et al. (2017); Mardani (2017); Li et al. (2018b)
Modified EDC (RANS)	Increased C_τ and/or decreased C_γ	Alleviated temperature over-prediction at axial location = 120 mm	De et al. (2011); Aminian et al. (2012); Shabanian et al. (2012); Evans et al. (2015); Tu et al. (2016); Li et al. (2018b)
	Modified C_{D1} and C_{D2}	- C_τ and C_γ changed accordingly - Capture the flame lift-off well	Mardani (2017); Parente et al. (2015)
Dynamic EDC (RANS)	Model constants determined locally and reacting fraction in fine structures χ = 1.0	Satisfactory prediction at various axial locations and generalized models	Parente et al. (2015); Evans et al. (2019)
—	local model constants with reacting fraction χ variation	Improved prediction compared to unifom χ = 1.0	Lewandowski and Ertesvåg (2018); Lewandowski et al. (2020b, a)
PaSR model (RANS)	Mixing and chemical time scales included explictly	Prediction at axial location $\geqslant$ 60 mm improved significantly compared to standard EDC	Li et al. (2017)
Dynamic PaSR model (RANS)	Dynamic mixing time scale	Improved prediction compared to standard PaSR, especially the high turbulence case	Li et al. (2018a); Ferrarotti et al. (2019)
Flamelet model (RANS)	—	- Computationaly efficient - Inadequate for JHC configuration	Shabanian et al. (2012); Christo and Dally (2005); Chitgarha and Mardani (2018)
Tabulated PSR model (RANS)	—	- Computationaly efficient - CO modelling is not satisfactory	Chen et al. (2017)
Transported PDF (RANS)	—	- Provide superior results - Computationally inefficient	Shabanian et al. (2012)
Conditional moment closure (RANS)	—	Conditional fluctuations of reactive scalars should be small enough for first-order closure	Kim et al. (2005)
Flamelet progress variable (LES)	—	- High workload for pre-processing - Largely increased table size with high dilution and heat losses - Less CPU hour needed	Ihme and See (2011); Ihme et al. (2012); Lamouroux et al. (2014); Locci et al. (2014)
PaSR (LES)	κ evaluated with mixing and chemical time scale	- No effort needed for pre-processing - Over-all good agreement - Compromise efficiency between tabulation based models and transported PDF model	Li et al. (2019)
Implicit models (LES)	κ = 1	- Similar performance as PaSR model - No need to estimate time scales	Li et al. (2019)

TABLE 2 | Absolute errors for temperature predictions (%) reported in literature with various combustion models

Models	Description	30 mm	60 mm	120 mm	Case	References
Standard EDC (RANS)	Standard constants	0.8	4.8	27.4	HM1	Aminian et al. (2012)
		8.2	10.6	25.7	HM2	
		5.8	8.2	20.2	HM3	
Modified EDC (RANS)	C_τ = 1.5	3.0	0.7	13.3	HM1	Aminian et al. (2012)
		1.3	2.9	13.1	HM2	
		2.0	0.5	9.5	HM3	
	C_τ = 3.0	7.9	6.0	0.4	HM3	Aminian et al. (2012)
	C_τ = 1.47, C_γ = 1.90	3.8	3.6	5.6	HM1	Parente et al. (2015)
	C_{D2} = 0.02	2.1	1.8	8.8	HM1	Mardani (2017)
	C_{D2} = 0.25	0.7	0.2	15.6	HM1	
	C_{D2} = 1.0	2.0	1.7	13.2	HM1	
	C_{D2} = 27	5.8	5.4	1.7	HM1	
	C_{D2} = 0.02	0.5	0.5	8.5	HM3	
	C_{D2} = 0.25	1.3	2.8	14.0	HM3	
	C_{D2} = 1.0	2.3	0.4	13.2	HM3	
	C_{D2} = 27	14.5	11.7	1.6	HM3	
Dynamic EDC (RANS)		3.48	1.75	9.35	HM1	Parente et al. (2015)
		1.84	4.37	2.27	HM2	
		8.56	10.49	3.08	HM3	
Flamelet model (RANS)		5.46	3.76	—	HM1	Chitgarha and Mardani (2018)
		13.7	8.03	—	HM3	

(FPV) formulation (tabulated based model) was employed by Ihme et al. (Ihme and See, 2011; Ihme et al., 2012) to model the JHC flame. Satisfactory agreement with the experimental data were obtained for mean temperature and major species mass fractions. While the use of FPV-based approaches in MILD combustion is promising, the highly diluted feature of MILD combustion often leads to high dimensional tables (Lamouroux et al., 2014; Locci et al., 2014), whose generation can be challenging and time consuming. Afarin et al. (2011) used PaSR to investigate the reaction zone structure and the distribution of temperature and minor species mass fractions, showing satisfactory accuracy. Li et al. (2019) presented a detailed comparison between the conventional PaSR model and two implicit combustion models, in which the filtered source term comes directly from the chemical term, without inclusion of turbulence effects. Results indicated that all three models could accurately predict the combustion of CH_4/H_2 in the JHC configuration, indicating that the sub-grid closure parameter κ played a minor role for the case under investigation. This suggested that, for low Damköhler number systems, the reacting structures can be potentially resolved on the LES grid.

A detailed comparison of different models applied on the JHC configuration is presented in **Table 1** and the prediction errors on several axial locations is summarized in **Table 2**. The errors reported in **Table 2** focus on the JHC burner with CH_4/H_2 50%/50% as fuel and with 3% (HM1)/6% (HM2)/9% (HM3) oxygen levels in the coflow. It is worth mentioning that at around 100 mm downstream of the jet outlet, entertainment from the surroundings tunnel air starts to have an effect on the flame (Dally et al., 2002).

CONCLUSION

The present paper reports a short review on the application of reactor based models to the simulation of a canonical MILD combustion system, the jet in hot coflow (JHC) burner. Successful predictions of JHC burner with finite-rate models were reported, with both Reynolds Average Navier-Stokes (RANS) simulation and Large Eddy Simulation (LES). The main conclusions drawn can be summarized as follows:

- The Eddy Dissipation Concept (EDC) model and its modified versions (with modified model constants) were first considered by most authors (De et al., 2011; Aminian et al., 2012; Shabanian et al., 2012; Tu et al., 2016; Mardani, 2017; Li et al., 2018a; Li et al., 2018b) for the prediction of a jet-in-hot-coflow (JHC) burner with RANS simulation. However, there is a lack of generality.
- The estimation of local EDC parameters based on the local turbulent Reynolds number and Damköhler numbers (Parente et al., 2015) could significantly improve the predictions in the context of MILD combustion, making the inclusion of chemical time scale (needed to estimate Damköhler number) important.
- In PaSR, the turbulence-chemistry interaction factor is based on a more general definition which requires the estimation of both chemical and mixing time scales. The choice of such scales has a crucial impact on the model prediction (Li et al., 2018a).
- A dynamic evaluation of mixing time scale in PaSR RANS formulation was proposed, presenting superior performance

than the other globally defined mixing models under a wide range of JHC flame operating conditions (Li et al., 2018a; Ferrarotti et al., 2019).
- The LES formulation of PaSR model along with other implicit combustion models show superior advantage for the prediction on the JHC flames (Li et al., 2019).
- Future studies shall focus on the generalisation and unification of reactor-based approaches, using available DNS data in MILD combustion (Minamoto and Swaminathan, 2015; Doan and Swaminathan, 2019) together with machine learning and optimization algorithms.
- Future studies should also target more complex fuels, such as oxygenated hydrocarbons and long-chain alkanes under MILD conditions. Because they have shown different characteristics, such as the appearance of visible flames and increased pollutant emissions, as indicated by (Weber et al., 2005; Saha et al., 2014; Ye et al., 2015b).

AUTHOR CONTRIBUTIONS

ZL wrote this paper. AP contributed to the paper conception and writing.

FUNDING

This project has received funding from the European Research Council, Starting Grant No. 714605, and the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 643134.

ACKNOWLEDGMENTS

Some sentences in the article were rephrased from the PhD thesis (Li et al., 2019) of the first author ZL.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.