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Influence of ethanol and EGR on laminar burning behaviors of FACE-C gasoline and its surrogate

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ABSTRACT

Laminar burning velocities of FACE-C gasoline and a surrogate comprised of toluene primary reference fuels (TPRFs) were investigated under the effects of EGR dilution and ethanol blending. Measurements were conducted in a spherical constant volume combustion chamber for a range of equivalence ratios from 0.8 to 1.6 at initial temperatures and pressures up to 383 K and 0.6 MPa, respectively. These measurements highlighted the effects of real combustion residuals (using combustion products directly) at mole fractions up to 0.3 and various volumetric percentages of ethanol blending. For both studied fuels, significant reductions in stretched and un-stretched flame speeds were observed for mixtures laden with real combustion residuals. Blends with less than 50% ethanol showed barely a minimal enhancement in the flame speed. By combining both EGR and ethanol blending, the flame speed reduction by EGR can be compensated for with ethanol addition. For example, up to 10% of EGR requires 60% ethanol blending to maintain the same flame speed. Flame stability enhancement by EGR addition was also quantified through the determination of the Markstein length.

1. Introduction

Despite the technological growth in alternative power systems for automotive applications, such as electric or hybrid engines [1], internal combustion engines will dominate automotive propulsion in the near future. Several technologies have been directed toward the advancement of gasoline engines for higher efficiency and lower emission including direct injection and downsizing [1].

Gasoline fuels composed of blends of hundreds of different hydrocarbons, which vary in composition depending on the source of crude oil, refining processes, and seasonal factors. As such, a quantitative comparison among experimental data among various laboratories was difficult. In this regard, Fuels for Advanced Combustion Engines (FACE) gasolines were developed based on statistical methods and mainly target values of research octane numbers (RONs) and fuel sensitivity to accommodate high efficiency advanced combustion engines [2]. A key aspect of these fuels is to allow researchers evaluating advanced combustion systems to compare results using the same sets of fuels for consistency [3]. Therefore, it is as indispensable as ever for these gasoline fuels and their components to be researched to gain fundamental understanding about combustion devices which they are fueled with. An accurate characterization of these fuels and in particular their flame propagation speed is essential and expedites modeling of their combustion behavior. The complexity of involving these fuels in either experimental or numerical studies stems from the fact that their kinetic, thermophysical and transport properties are variable and often ill-defined [4]. Moreover, developing robust chemical kinetic mechanisms of these multi-components fuels that would represent the oxidation of hundreds of different hydrocarbons from different molecular classes with accompanying chemical reactions is not feasible with the status quo of computational capabilities and chemical kinetic knowledge. Therefore, as a promising approach to overcome this difficulty, it is frequently desirable to use less complex fuels as a gasoline surrogate that can emulate its combustion characteristics, which include laminar burning velocities[5, 6], ignition delays [7], engine ignition phasing [8], and pollutant emissions [9].

Furthermore, they possess numerous advantages over real fuels such as reproducibility and possibility of formulating chemical models for high fidelity computational tools.

Recently, various surrogate fuels have been recommended and their properties have been extensively reviewed [4]. The complexity of surrogate formulation varies according to which practical application they are targeting. For example, binary blends of Primary Reference Fuels (PRFs), namely *iso*-octane and *n*-heptane, are known as the simplest surrogates for RON and MON tests to quantify the knock resistance of a gasoline by matching their knock intensities in a standard engine. Detailed [10, 11], semi-detailed [12, 13] and reduced [5, 14-16] chemical mechanisms for PRF combustion have been well developed and validated. One key aspect of gasoline characteristics is its sensitivity S , i.e., the difference between RON and motor octane number (MON) ($S = \text{RON} - \text{MON}$), which quantifies the sensitivity of the fuel response to lower pressures and higher temperatures. By definition, PRFs have zero sensitivity, while a real gasoline is expected to exhibit different anti-knock properties in a MON test from those of a PRF of equivalent RON, thus having a non-zero sensitivity. For this reason, toluene primary reference fuels (TPRFs), ternary blends of *iso*-octane, *n*-heptane, and toluene, have an advantage of non-zero sensitivity and an ability to match the anti-knock properties at both pressure-temperature conditions for RON and MON tests. Additionally, *n*-heptane and *iso*-octane have H/C molar ratios of 2.29 and 2.25, respectively, while that of commercial gasoline is about 1.87. The local fuel/air ratio is a function of the H/C molar ratio, among other variables, and hence the difference between PRF and gasoline in this respect makes it an unsatisfactory surrogate fuel in some applications. Recently, binary blends of toluene with either *iso*-octane or *n*-heptane offer a potential to isolate their cross-oxidation chemistry, however such blends have been found to be of a very limited application as gasoline surrogate. The involvement of *iso*-octane and *n*-heptane as major components of a surrogate is inevitable as they represent linear and branched alkanes which are major gasoline components [17]. However, gasoline does contain more chemical species than just alkanes. Recent European and American standards of gasoline require specific aromatic content and also allows for the involvement of

oxygenated fuels, such as ethanol. Consequently, it seems reasonable to continuously exert efforts in seeking gasoline surrogates beyond PRFs and even sometimes beyond TPRFs which contain compounds approximating various families of hydrocarbons present in gasoline. On that account, a blend of TPRF (77.40% *iso*-octane + 17.60% *n*-heptane + 5% toluene) mixture was developed [6] to alleviate the complexity of incorporating multi-component FACE gasoline fuel into combustion modeling. Following the course of the study in [6], the effects of ethanol addition on laminar burning characteristics of FACE-C and its developed surrogate were investigated by varying the equivalence ratios ϕ and initial pressures P_0 in the present study

Burning characteristics and combustion modeling in the aforementioned advanced combustion engines requires comprehensive accurate data for laminar burning velocities which will also contribute to the development of reliable chemical mechanisms for the combustion of certain fuel-air mixtures over a wide range of thermodynamic conditions (*i.e.*, ϕ , P_0 , and initial temperatures T_0).

Exhaust gas recirculation (EGR) is a widely used concept of reducing NO_x emissions and throttling losses in internal combustion (IC) engines [18-20]. Recent studies have shown that further reduction in combustion temperatures, using very high rates of cooled EGR, can further diminish or even completely eliminate soot production [21-24]. Note that cooled real EGR acts as a diluent and coolant without altering the stoichiometry as opposed to either running lean or over-fueling. Despite the abundance of studies conducted on the effect of synthetic exhaust gas recirculation (EGR) on laminar burning velocity, the impact of real (non-synthetic) combustion residuals (utilizing combustion product directly for EGR) is limited. Metghalci and Keck [25] synthetically diluted stoichiometric mixtures with 15%/85% blend of CO_2/N_2 up to diluent mass fractions (x_r) of 0.1 and 0.2 and further extension of x_r up to 0.3 was approached in the work by Ryan and Lestz [26]. Rhodes and Keck [27] studied indolene-air flames diluted by volume fractions up to 30% of a 20/80 %vol of synthetic blend of CO_2/N_2 for a wide range of equivalence ratios. Jerzembeck *et al.* [5] approximated the effect of EGR dilution by reducing

the O₂ concentration in synthetic air. Fuller *et al.* [28] examined the role of vitiated air on laminar flame speeds of *n*-decane through the introduction of CO₂ and H₂O to the oxidizer stream. Foucher *et al.* [29] explored the effect of CO₂, H₂O and synthetic EGR dilution of the laminar burning velocities and stability characteristics of iso-octane/air flames. Therefore, while there is a plethora of studies concerning the effects of synthetic dilution on the laminar burning velocity, until now there has been a limited data concerning the fundamental knowledge of laminar burning velocity under moderately cooled temperature highly diluted real EGR conditions. Although simulation studies have investigated the behavior of air diluted flame front in the spark-assisted compression ignition regime [30], additional fundamental insight is needed under relatively practical operating conditions. Note that experiments have been mainly conducted with synthetic residuals, which are mixtures of inert gases. While the specific heat capacity of real combustion residuals may vary with equivalence ratio and may contain water vapor and non-inert gases such as unburned hydrocarbons, hydrogen and carbon monoxide. To the author's knowledge, only a single study of real trapped combustion residuals in a combustion vessel was conducted by Marshall *et al.* [31] to investigate *iso*-octane flames diluted up to 30 %.

As cooled EGR expectedly suppresses the burning rate and can compromise combustion stability, effects that can be attributed to the reduction of oxygen concentration of the combustion gases and the existence of CO₂ and other products that slow down the reactivity of the mixture, a remedy that compensates for such adverse effects is continuously under investigation. Alcohol additives can be one of the proposed solutions to counteract the disadvantages imposed by the presence EGR during the combustion process. Ethanol is an alternative and complementary biofuel to gasoline that can significantly affects its burning characteristics [32, 33]. The importance of ethanol arises from the global warming issue together with energy security. It has somewhat similar stoichiometric laminar burning velocities to gasolines, but it is not as prone to knocking [34, 35]. Furthermore, ethanol has a higher extinction strain rate than *iso*-octane [36] which renders it to be favored in highly turbulent flames as it effectively reduces localized flame extinctions and increases the potential of easy re-ignition [37-39].

Also, it contributes to the means of reducing engine emission, in particular CO and PM emissions [40]. Furthermore, increasing ethanol content can yield a NO_x reduction due to the decrease in local flame temperature [41].

The present work provides a complement to experimental database for FACE-C and its developed surrogate provided by Manna *et al.* [6] by highlighting the influence of real combustion residuals on the laminar burning characteristics of FACE-C gasoline fuel (RON 85) and its developed surrogate of toluene primary reference fuel (TPRF) at ambient and elevated pressures and temperatures. Also the combustion characteristics of different binary blends of ethanol with FACE-C gasoline or its developed surrogate (TPRF) with and without real combustion residuals are investigated. These data are used to derive correlations for the laminar burning velocity, required for combustion modeling in developing predictive tools for combustion in IC engines. Further, the effects of initial temperature and pressure are studied for the purpose of proposing correlations to allow extrapolations to high pressure and temperature conditions, which are typically unattainable experimentally due to safety limitations. To test the predictability of the effects of real EGR and ethanol through a computation, 1-D planar flame simulations using the PREMIX code [42] were performed and compared with experiment at wide range of experimental conditions. In addition, stretch rate effects and the onset of flame instabilities were examined via the derivation of the Markstein length.

2. Experimental apparatus

Flame propagation experiments were conducted in a spherical constant volume combustion chamber made of stainless steel with an inner volume of 20 L (inner diameter $D_c = 330$ mm). Details of the experimental setup were reported previously [6]. The apparatus is optically accessible through two orthogonal pairs of quartz windows (diameter $D_w = 120$ mm). Such large windows ($D_w/D_c \approx 0.36$) enabled the observation of stable flame propagation for a relatively long period after ignition transient until the effect of wall-confinement through pressure rise. As discussed in detail in our previous study

[6], a large volume of the spherical chamber mitigated the sensitivity on the choice of either linear or non-linear extrapolation method in the determination of un-stretched laminar burning velocity. Detailed descriptions of the auxiliary equipment along with the experimental apparatus, procedure and post-processing of data were presented previously [6].

The chamber is capable of withstanding the pressure after flame propagation for the initial pressure, P_0 , up to 1.0 MPa for the initial temperature, T_0 , up to 400 K. The initial gas temperature was monitored by two Chromel-Alumel K-type thermocouples (sheathed with 1.5 mm diameter stainless tube). Gas-tight syringes (5, 10 and 50 cm³) were integrated to the chamber through a needle valve for liquid fuel injection. The amount of liquid fuel required corresponding to an initial condition (ϕ , P_0 , T_0) was calculated from the partial pressure and fuel density. Fuel was injected under a vacuum condition of approximately 0.001 MPa. A pressure transducer (Keller, PAA-33X) monitored the partial pressure of the reactant during the mixture preparation as well as the initial pressure prior to ignition. A second dynamic pressure transducer (Kistler, 605A) was used to determine the temporal pressure evolution during the combustion phase. The mixture was ignited centrally using V-shaped two electrodes connected to a high voltage power supply (TREK, 40/15-H-CE), which was controlled by a function generator (Tektronix, AFG3021B) [6]. Direct visualization of flame initiation and development was captured using an inline lens-based Schlieren cine-photography system. The monochromatic images of a propagating flame were captured using a high-speed camera (Photron, FastCam Ultima APX 120K with 10-bit resolution, 512×512 pixels) typically at 4000 fps with 0.315 mm/pix resolution.

For fuel-air flame experiments, the combustion vessel was purged with nitrogen to assure a proper scavenging of combustion residuals from previous experiment. For a real EGR experiment, a preliminary deflagration corresponding to a desired equivalence ratio was conducted and a trapped portion of the resultant combustion products were retained for the following fuel-air-EGR flame experiments. Note that in an internal combustion engine, residual gas is influenced by crevice volumes and wall quench layers. For the present spherical vessel with a large inner diameter, the effect of quench

layer is expected to be small. Thus, the present residual gas can be considered as originated from the main combustion zone.

Details of auxiliary equipment integrated with the vessel, operating procedures, and post-processing data methodology are illustrated in [6, 43]. In the present study, the equivalence ratio ϕ of the injected fuel-air mixture was checked via feeding the combustion products past two systems, namely a lambda sensor (ECM, AFRecorder 5220) and a gas analyzer (Horiba, VA-3000). The first technique measures lambda ($1/\phi$) while the second one measures CO₂, O₂ and CO species concentrations through a dry-base calculation.

3. Data reduction of spherically expanding flames

Several algebraic expressions for deducing laminar burning velocities from spherically expanding flames have been presented and widely adopted in the literature [32, 44]. In order to post-process Schlieren image set of an expanding flame, a number of Matlab automated batch processing tools were utilized. First, an in-house Matlab code was developed to mainly track the temporal evolution of flame contour and subsequently deduce the instantaneous mean flame radius. An image was binarized using an optimum threshold value to have a white flame image surrounded by a black background. The Matlab script counted the white pixels which yield the flame area and mean flame radius, based on a spherical flame assumption.

The directly measured temporal evolution of flame radius ($R_f(t)$) was used to calculate the instantaneous stretched burnt gas velocity as follows:

$$S_b = dR_f/dt \quad (1)$$

Afterwards, S_b has to be corrected for the effects of stretch rate, κ , given by $(1/A) (dA/dt)$, where A is the flame surface area and t is the time [45]. For a spherical expanding flames, this gives [46]

$$\kappa = (2/R_f) S_b \quad (2)$$

The stretch effect on flame speed was systematically identified using asymptotic analysis, yielding the linear model of extrapolating the flame speed to a zero stretch rate. The equation reads [47-50]

$$S_b = S_b^0 - L_b \kappa \quad (3)$$

where S_b^0 and L_b are the un-stretched laminar flame speed and the Markstein length with respect to burnt mixtures, respectively. This relation was further examined by Kelley *et al.* [51] to a non-linearly extrapolated stretched flame speed as

$$(S_b/S_b^0)^2 \ln(S_b/S_b^0)^2 = -2L_b \kappa / S_b^0 \quad (4)$$

In addition, another nonlinear extrapolation was suggested by Chen [52] as

$$S_b = S_b^0 - L_b \kappa = S_b^0 - 2L_b S_b^0 / Rf \quad (5)$$

The unburned un-stretched laminar burning velocity is obtained through the continuity.

$$S_b^0 \rho_b^0 = S_u^0 \rho_u \quad (6)$$

Here, ρ_b^0 and ρ_u are the burnt and unburned densities of the mixture, respectively, and are computed using Gaseq software [53] and EQUIL CHEMKIN module implementing STANJAN for computing chemical equilibrium [54].

4. Results and discussion

The present study aims to characterize the laminar burning characteristics of FACE-C gasoline and its corresponding surrogate TPRF (17.60% *n*-heptane + 77.40% *iso*-octane + 5% toluene) [6], both having the RON of 85 [3, 55], under the effects of real combustion residuals. The effect of ethanol addition is studied for a wide range of either ethanol/FACE-C or ethanol/TPRF blends. The combined effect of ethanol and EGR on their laminar burning characteristics is also examined. Table 1 lists the test matrix of fuels investigated and their fuel indices.

4. 1. *Flame visualization*

The Schlieren images (flame radius $R_f \approx 45$ mm) reveal flame morphology details as shown in Fig. 1, corresponding to atmospheric F-C/air and TPRF/air flames (first and second columns) and high pressure TE60/air and FE60/air flames (third and fourth columns) diluted at several mole fractions of combustion residuals (x_r). The equivalence ratio was fixed at a slightly rich condition of $\phi = 1.1$. The result indicates that for the cases having EGR up to say $x_r = 0.2$, the flame sphericity was relatively well maintained, while for the case with $x_r = 0.3$, the flame moves upward by the buoyancy, especially at high pressure with slowly burning cases. Note that the laminar burning velocity generally decreases with pressure. Thus, for the high pressure and high EGR cases, the time required for the flame radius to reach about 45 mm is about 100 ms, which may be sufficiently long to induce the buoyancy effect. Also note that the flames with high EGR addition ($x_r = 0.3$) become occasionally susceptible to either ignition failure or incomplete flame propagation. The atmospheric flames exhibit smooth and stable flame morphology. However, as P_0 increases, cellular structures develop, especially with high ethanol content. In such a case, however, EGR influences the developing degree of flame cellularity. As EGR increases, the development of cellular structure is mitigated across the flame front morphology.

4. 2. *Dynamic behavior of spherically propagating flame*

Typical variations of stretched flame speed, S_b for $\phi = 1.1$ flames are shown in Figs. 2 and 3 as a function of flame radius at $T_0 = 358$ K for TPRF/air (2a), TE60/air (2b) at $P_0 = 0.1$ and 0.6 MPa with $x_r = 0$ and 0.1. Figure 3 depicts these variation for various TPRF-ethanol/air blends at $P_0 = 0.6$ MPa. Here, the stretched flame propagation speed with respect to the burnt gas, S_b , is defined as the time rate of change of flame radius, dR_f/dt , with $R_f(t)$ being the measured flame radius determined from the experimentally recorded Schlieren image. All these cases exhibit three regimes [56]. The initial high flame speeds

(regime I) can be attributed to a deposition of ignition energy that is high enough to over-drive a flame. As the effect of ignition energy decays, the flame speed boosted by spark energy decreases rapidly and then starts to approach a steady behavior known as normal flame chemistry regime (regime II). The range of this stable, stretched flame regime can be identified in Fig. 2 (as will be shown later, such effect can be more pronounced when plotting flame speed against flame stretch rate in Figs. 4 and 5). In all these figures the inner, high stretch rate, limit is indicated by #. As the radius of expanding flame becomes large, a relatively rapid increase in S_b can be observed (regime III). This can be attributed to the promotion of intrinsic flame front cellular instabilities (by hydrodynamic and/or diffusional-thermal instabilities). Similarly, in all these figures, the inception of flame instability is marked by X. Interestingly, EGR decreases not only those values of S_b but also such rapid increase in S_b as shown in Fig. 2(a, b), while ethanol addition enhances S_b as shown in Fig.3.

At high pressure and rich fuel mixture with large carbon numbers, a cellular structure can be developed that is manifested as small scale mottling covering the entire flame surface [44]. In such a case, S_b has a propensity to encounter an abrupt acceleration at later stages of propagation due to an increase in topological flame surface area.

The dynamics of expanding spherical flame can be clearly manifested through the temporal variations of stretched flame speed, S_b , against the overall stretch rate, $\kappa = \frac{2}{R_f} S_b$. Similar to the spatial variations of S_b with R_f shown in Figs. 2 and 3, three regimes can be identified for the dependency of S_b on κ as shown in Fig. 4. These regimes are that of spark ignition at initial flame development, the regime of flame propagation influenced by the stretch rate, and finally the unstable regime of flame cellularity. Similar to Figs. 2 and 3, the boundaries, separating the spark affected regime and the development of a wrinkled cellular structure regime are marked by labels #, X, respectively. This first boundary of the

linear regime (Regime II) used for correcting the flames speed from stretch effect, is demarked based on the computational study conducted by Bradley *et al.* [57] showing the independence of flame propagation from the ignition effects at radii larger than 6 to 10 mm. While the end boundary demarcates the sharp increase in flame speed due to the full development of cellular structure across the flame front. These limits seemed reasonably appropriate for the present experiment. For the sake of pictorial clarity, the application of different extrapolation models is only shown in Figs. 4 and 5 for one case trial. Due to the large radius of the chamber ($R_c = 165 \text{ mm} > 100 \text{ mm}$), the accuracy of the flame speed measurements in the present work suffer a minimal compression effect of about below 5 % [44, 58-62]. Note that since the normalized flame radius R_f/R_c is less than 0.5, the pressure increase in the pre-pressure rise period is below 15% and in turn the temperature rise of the unburned mixture is less than 12 K. Consequently, the change in the measured laminar flame speed does not exceed 1% and thus reasonably is negligible [63]. As such, the lower and upper bounds of flame radius range utilized for the derivation of S_b [1 cm, 4.5 cm] renders the linear extrapolation to zero stretch rate fairly accurate [6, 63].

Figures 2 and 4 clearly highlight the interplay between the effects of combustion residuals on S_b of F-C and its surrogate TPRF and one of their blends with ethanol, namely TE60 and FE60. A mole fraction of $x_r = 0.1$ causes about 33% and 50% reduction for $\phi = 1.1$ at 0.1 and 0.6 MP, respectively. This can be attributed to the following: (1) the reduction of O_2 concentration by residuals presence. The displacement of O_2 by exhaust gases decreases the oxygen partial pressure affecting the kinetics of NO_x formation reactions [64]; (2) the thermal effect induced by the existence of EGR and its two major constituents, namely carbon dioxide and water vapor. The presence of tri-atomic molecules such as CO_2 and H_2O which act as ballast gases due to their high specific capacities and therefore lessens heat release intensity and the probability of fuel molecules to be attacked by oxidizer ones. Consequently, the local peak temperature in the flame decreases within the reaction zone, which not only reduces the rate of formation of NO_x but also results in an appreciable reduction in the propagating flame speed; and (3) the chemical effects resulting from the presence of H_2O and CO_2 . These gases undergo dissociation during

combustion, altering both the chemistry of the combustion process and formation of NO_x . Particularly, the flame temperature is drastically moderated by the endothermic dissociation of H_2O [64].

Effects of different ethanol volume fraction on S_b of F-C and corresponding TPRF surrogate are also shown in Figs. 3 and 5. Clearly, the enhancement effect is barely noticeable up to 45% and becomes conspicuous as the ethanol volume fraction is extended up to 60% and beyond. Although adiabatic flame temperature, T_{ad} , has a significant influence on the laminar burning velocity [65-67], and ethanol has a lower T_{ad} [68, 69] due to its lower heating value, Q_{LHV} , and its lower C/H atom ratio, the presence of an oxygen in its molecular structure significantly increases laminar flame speed.

As previously mentioned, regime III in Figs. 3 and 5 characterizes the augmentation of flame speeds caused by the unstable flame morphology of cellular structure. Apparently, the presence of exhaust gases during combustion period suppresses the inception of this regime. In other words, flame stability is enhanced by recycling a fraction of exhaust gases from the exhaust to the intake system.

4. 3. *Effect of EGR and ethanol addition on laminar burning velocities*

The stretched flame speed was corrected for stretch effects using linear extrapolation to derive the un-stretched burnt laminar burning velocity, S_b^0 and then corrected for the density ratio, ρ_b^0/ρ_u , across the flame to obtain the un-stretched unburned laminar burning velocity, S_u^0 . Variations of unstretched laminar burning velocities, S_u^0 , for fuels listed in Table 1 are shown in Figs. 6-11 at $T_0=358$ K and $P_0=0.1$ and 0.6 MPa. All S_u^0 data are listed in the supplementary file.

As reported in detail in our previous study [6], Figs. 10 and 11 highlights the satisfactory agreement of S_u^0 between F-C and its developed surrogate at atmospheric and elevated pressures and a wide range of equivalence ratios. Additionally, the measurements cover a wide range of equivalence ratios for ethanol and two ethanol blends with both F-C and its TPRF surrogate as shown in Figs. 6-9. The error bars shown in these figures quantify the uncertainty in S_u^0 due to not only experimental

repeatability but also different extrapolation models [70] discussed in section 3 and shown in Figs. 6-11. Regarding the cases which the flame suffers appreciable buoyancy effects due to slow burning cases as depicted in Fig. 1, a radiation-corrected flame speed was examined using the proposed expression in [71]. However, due to the large vessel size and the maximum observable ratio of flame radius to vessel radius of 0.36, the difference between corrected and non-corrected flame speed for radiation does not exceed 4%. The error bars shown in the plots indicate the uncertainty associated with S_u^0 and ϕ . Uncertainties in the determination of S_u^0 comes from experimental configuration and a method of extrapolating data to zero stretch rate, particularly at low pressure [70, 72]. Other effects, such as ignition [51, 73-75], flow confinement [51, 76, 77] and radiation [71, 78, 79] could also influence the result. Note that the significance of each source of aforementioned uncertainties is largely dependent on the size and geometry of vessel and experimental conditions. A detailed discussion has been presented previously [6].

As depicted in Figs. 6, 7, 8 and 9 the role of ethanol as an accelerator fuel in the ethanol blends (FE60, FE85, TE60, and TE85), respectively can be manifested. Note that the effect of ethanol addition in enhancing S_u^0 is more distinguished for atmospheric pressure flames shown in Figs. 6 and 8. Simulation results of 1-D planar TPRF, TE60 and TE85 flames, shown in Figs. 8 and 9, utilizing the PREMIX code (CHEMKIN) were obtained using Mehl's chemical oxidation mechanism [80]. The simulated results show, to some extent, a satisfactory agreement with the experiments for the lean and near stoichiometric flames, while the agreement slightly deteriorates at high pressure for $\phi > 1.0$.

Figure 12 shows the variation of S_u^0 for various ethanol percentages blended with F-C and TPRF ($\phi=1.1$) at $T_0=358$ K and $P_0=0.1$ and 0.6 MPa. Clearly, ethanol produces a significant synergy in the laminar burning velocities of both F-C and TPRF with high level of ethanol blending. The synergistic effect of ethanol is more pronounced in boosting low pressure flames compared with high pressure ones. At low and medium ethanol mole fractions, the enhancement in combustion gained by oxygen

availability is offset by its lower enthalpy of combustion. Consequently, the enhancement in the laminar burning velocity as a result of adding ethanol to the fuel blend will not have any apparent effect until high ethanol content (ethanol % > ~45).

Influence of real combustion residuals on S_u^0 for F-C/air and TPRF/air flames is shown in both Figs. 10 and 11. Seemingly, the decrease in S_u^0 caused by 10% EGR has a weak dependence on the equivalence ratio for both fuels regardless of the initial pressure condition. To further explore the difference between real and synthetic EGR and assure the fidelity of utilizing artificial EGR as a benchmark in the future studies to simulate real ones, a synthetic EGR mixture of CO_2 and N_2 were tested with atmospheric TPRF and F-C flames shown in Fig. 10. The portions of CO_2 and N_2 were determined based on the ratio of CO_2 to N_2 corresponding to the desired equivalence ratio derived from equilibrium calculation conducted using CHEMKIN. Clearly, synthetic EGR induces relatively more reduction in the laminar burning velocities of both F-C and its surrogate TPRF compared to real EGR. Such difference can be attributed to the distinctive difference in EGR composition between synthetic and real one. Real EGR constituents (the data provided in the supplementary file) are CO_2 , H_2O , O_2 , N_2 , and other non-inert trace gases such as hydrogen and carbon monoxide, while artificial EGR usually contains the two major inert components which are CO_2 and N_2 [31]. Consequently, the dilution, chemical and thermal effects of the admission of both synthetic and real EGR into the fresh combustible charge will be distinguishable.

Although combustion products vary with the equivalence ratio, it has been reported in [81, 82] that the specific heat C_p of combustion products can be approximated to 1 kJ/kg K. A stoichiometric case was selected and C_p was calculated for both real and synthetic EGR. For real EGR, O_2 , N_2 , CO , CO_2 , H_2O , and CH_4 were included in the calculation, while synthetic EGR only includes N_2 and CO_2 . The specific heat of real EGR was $C_p \approx 1.13$ kJ/kg K, while synthetic one was 0.96 kJ/kg K. Regardless of the small difference between the two values, based on the thermal effects alone caused by C_p , real EGR supposedly should cause more reduction of flame speed as they have slightly larger C_p , but this is not

the case in this study which shows the opposite trend. Accordingly, both kinetic and thermal effects should be taken into consideration when studying the effect of dilution on flame speed [28].

To verify the invariance of mixture's stoichiometry with the admission of EGR into the fresh combustible mixture, detected ϕ was recorded by sampling the product gases into two different paths simultaneously through the gas analyzer and the lambda sensor. Table 2 shows the minimal variation between the calculated and the detected equivalence ratios through both the gas analyzer and lambda sensor, respectively. Also depicted in Fig.10, simulated 1-D results for EGR-diluted TPRF/air mixtures were also obtained using Mehl's mechanism [80]. This is implemented by utilizing the mole fractions of complete equilibrium combustion products associated with the specified equivalence ratios obtained by EQUIL module in CHEMKIN to closely simulate the presence of real combustion residuals. The simulated results for atmospheric flames are in relatively satisfactory agreement with experimental values. On the other hand, as depicted in Fig.11, for high pressure flames, the reasonable agreement is still maintained for lean flames while it noticeably deteriorates for rich ones.

The influence of mole fraction of real combustion residuals on S_u^0 of F-C and TPRF is manifested in Fig. 13, where S_u^0 decreases monotonically as x_r increases. For all tested fuels, the flame speed decreases reasonably quasi-linearly with the dilution ratio, contrary to the nonlinear correlations suggested in the literature between the laminar flame speed and the dilution ratio, even at low and moderate levels of dilution [83-86]. On the other hand, this trend agrees reasonably with previous studies [30, 87-89]. As previously mentioned, this can be attributed to the so-called "EGR burning rate reduction mechanisms" which can be categorized according to the induced dilution, chemical and thermal effects on the burning rate of reacting flame front [18, 30]. Thermodynamically, the recirculation of exhaust gases boosts the average heat capacity of the fresh charge relative to atmospheric air due to the higher specific heat capacities of CO_2 and H_2O in the trapped exhaust gases relative to the heat capacities of the nitrogen and oxygen they replace. Therefore, the reduction in local

flame temperature increases as x_r increases rendering the combustion heat to be absorbed by a larger mass of high specific heat gases. Chemically, the admission of EGR to the fresh mixture causes the replacement of O_2 and N_2 concentrations in the fresh charge with constituents contained in the exhaust gases, specifically, CO_2 , H_2O , O_2 , N_2 and other trace gases such that the fresh mixtures becomes deficient of O_2 . Moreover, the chemical effect of EGR focuses upon the participation of free radicals that may form from the dissociation of the recirculated CO_2 and H_2O at the higher combustion temperatures [90]. Hence, as predicted in [28], the presence of CO_2 and H_2O may adversely affect the overall radical concentration emanating from chain-branching reactions. Experimental attempts were made for mole fraction of EGR beyond 0.3, but for these low flame temperature cases, reaction rates were too low to maintain a steady reactive-diffusive front structure and the front ultimately succumbed to bulk quenching.

Based on the effect of pressure on S_u^o , the variations of S_u^o with pressure were interpreted through an empirical correlation in the form of $S_u^o/S_{u, datum}^o = (P/P_{datum})^\beta$, where the subscript datum indicates datum values at 0.1 MPa and 358 K. Figure 14a shows such correlations for the lean, stoichiometric and rich TE60/air flames at $T_0 = 358$ K. The parameter β is dependent on the overall reaction order, n , ($\beta = n/2 - 1$), that is generally smaller than 1.5 for hydrocarbons [91]. Different values of pressure coefficient β are obtained depending on equivalence ratio [25, 44, 92]. β increases as the equivalence ratio decreases, a trend that has been reported by Bradley *et al.* [32] and Marshall *et al.* [31]. Similar values of β were obtained by Bradley *et al.* [32] for neat ethanol/air mixture indicating their insensitivity to blending, as in the present study. Also comparable values were derived in [6, 88] for the same surrogate, namely TPRF without the ethanol addition manifesting the inconsequential influence of ethanol addition as an alcohol fuel on β .

Similarly, the measured values of S_u^o for 0.2 MPa at various temperatures for lean, stoichiometric, and rich TE60/air flames were correlated by an assumed empirical correlation in the form of $S_u^o/S_{u^o \text{ datum}} = (T/T_{\text{datum}})^\alpha$. The datum here indicates values of S_u^o at 0.2 MPa and 313 K. Figure 14b illustrates the effect of unburned gas temperature on normalized laminar burning velocity. For larger values of T_0 , the dependence of flame speed on initial temperature is more sensitive because of the Arrhenius factor [66]. The temperature coefficient, α , reveals an appreciable decrease in its value as ϕ increases. Values of α are quite close to those measured in [32] for ethanol/ air mixture which manifest the insensitivity of temperature coefficient to the blending effect.

These β and α exponents are suggested to be critical inputs in predicting the initiation criterion of pre-ignition in [93], where there has been an emphasis on establishing rigorous values of β and α for different fuels.

In order to characterize the effects of EGR and ethanol addition on the burning rate of the studied fuel/air mixtures, the temporal evolution of the dynamic pressure during the flame propagation was monitored using high frequency piezoelectric pressure transducer. It is usually assumed that the fractional pressure rise is proportional to the fractional mass burned [19]. The importance of pressure time history stems from its inclusion in determining the burning rate or rather the reactivity of fuel/air mixture and also recently being widely adopted in testing octane sensitivity of different fuel/air mixtures. Furthermore, the pressure traces of different experimental runs corresponding to the same experimental conditions can determine the level of repeatability achieved of the extracted results. Figure 15a highlights the temporal evolution of pressure inside the chamber during the combustion of stoichiometric atmospheric F-C/air flame and its TPRF surrogate at neat and EGR-diluted conditions. Remarkably, the pressure trace of F-C closely matches its TPRF counterpart which signifies the validity

of TPRF to behave as a developed surrogate for F-C. Furthermore, as depicted in Fig. 15a the lag in combustion progression caused by 0.1 mole fraction of EGR is almost the same for both F-C and its developed surrogate. Noticeably, the lag in combustion development increases as the pressure increases which is manifested in Fig. 15b. Such retardation in the combustion progress of high pressure EGR diluted flames can be attributed to kinetic effect induced by EGR addition. To illustrate the effect of increasing EGR dilution ratio, the pressure traces of slightly rich TPRF/air flame ($\phi = 1.1$) at various x_r were captured at atmospheric pressure as shown in Fig. 15c. As previously verified through the visual schlieren measurements as x_r increases, the rate of combustion progress drastically drops off. Figure 15d highlights the effect of various ethanol additions on high pressure slightly rich TPRF flame. Interestingly the pressure traces capture the weak sensitivity of burning rates to ethanol addition, in particular at elevated pressure ($P_0 = 0.6$ MPa).

4. 4. Flame instability

Flame instability can be quantified by estimating the Markstein length, L_b , extracted from the slope of linear regime II (refer to Fig. 4b). Figure 16 shows the variation of L_b for F-C and its surrogate TPRF versus a wide range of equivalence ratios at $P_0 = 0.1$ and 0.6 MPa. It is obvious that the Markstein length is strongly dependent on the initial pressure and the equivalence ratio of the combustible fuel/air mixture but the combustion residuals has also a specific effect. Because the fuels are heavy hydrocarbons, the Markstein lengths of flames with and without combustion residuals decrease monotonically as the mixture becomes richer. Noticeably, as shown in Fig. 10a, the Markstein lengths for mixtures laden with combustion residuals are significantly higher than their counterparts without combustion residuals. This reveals that EGR promotes the stabilizing effect of flame stretch on flame propagation, which has been discussed previously in Fig. 1 concerning the delay of the appearance of flame cellularity and flame crack (cell) size captured in the Schlieren images. Such flame stability enhancement has been observed by Foucher *et al.* [29, 94] characterizing the effect of CO₂, H₂O and

synthetic EGR for iso-octane/air mixtures. Also, Ravi *et al.* [95] reported an increase in the magnitude of Markstein length due to N₂ addition and hence the flame becomes more sensitive to flame stretch stabilizing effects. Noticeably, the effect of EGR is more pronounced for the lean mixtures than the rich ones, indicating higher sensitivity for its stabilizing effect for lean flames. The interaction of different rate of real EGR (x_r) and volume fractions of ethanol on slightly rich TE60 and TPRF flames is highlighted in Figs. 17a and 17b, respectively. Clearly, the flame stability of TE60/air flame is augmented through the noticeable increase in L_b as x_r increases. However, as the initial pressure increases, less rising of the Markstein length is noticed. Such trend is also in good agreement with Foucher *et al.* [29]. Also, for TPRF/air, the role of ethanol in enhancing the flame speed is discernible for mixtures containing more than 50% ethanol. This can be justified based on the large values of Lewis numbers of mixtures containing large volumetric fractions of ethanol. However, the increase of the initial pressure demonstrates insensitivity of this Markstein length with the ethanol content.

5. Concluding remarks

Measurements of laminar burning velocities of FACE-C gasoline and its TPRF surrogate were conducted to illustrate the respective effects of real combustion residuals and ethanol blending, along with the combined effects. The merit of the measurements can be appreciated in the recent interest in dual fuel systems, where gasoline as primary fuel, and ethanol as a secondary fuel. Also, experimental measurements that involve the effect of real EGR on laminar burning characteristics can be used for validation of vitiated kinetics. Noticeable enhancement of laminar flame speeds was observed for blends with high ethanol content. For tests with real combustion residuals, the reduction of laminar burning velocity of both fuels showed insensitivity to the variation of equivalence ratio. This reduction is attributed to the presence of high specific heat capacity combustion residuals and tri-atomic dissociation of primarily carbon dioxide and water. Atmospheric flames were tested with synthetic EGR and exhibited more reduction in their flame speed compared to real exhaust residuals due to the reductive

composition of artificial EGR. Sixty percent ethanol blends of either gasoline or its surrogate seem to counteract the reduction of flame speed caused by 10% EGR. Values of pressure and temperature exponents were obtained through derived empirical correlations manifesting their insensitivity to blending effect, namely ethanol addition. With respect to flame stability, real combustion residuals promoted flame stability of both fuels indicated by a noticeable increase in the Markstein length, particularly for lean flames. However, as the mixture becomes richer, the enhancing effects of EGR addition diminished.

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References

1. M. J. Atkins; C. R. Koch, in: SAE Technical Paper: 2003-01-0081.
2. S. M. Sarathy; G. Kukkadapu; M. Mehl; W. Wang; T. Javed; S. Park; M. A. Oehlschlaeger; A. Farooq; W. J. Pitz; C.-J. Sung, Proc. Combust. Inst. 35 (1996) 249-257.
3. W. Cannella; M. Foster; G. Gunter; W. Leppard, CRC Report No AVFL-24 (2014).
4. W. J. Pitz; N. P. Cernansky; F. L. Dryer; F. Egolfopoulos; J. Farrell; D. Friend; H. Pitsch, in: SAE Technical Paper: 2007-01-0175, 2007.
5. S. Jerzembeck; N. Peters; P. Pepiot-Desjardins; H. Pitsch, Combust. Flame 156 (2) (2009) 292-301.
6. O. Manna; M. S. Mansour; W. L. Roberts; S. H. Chung, Combust. Flame 162 (6) (2015) 2311-2321.
7. A. Babajimopoulos; G. A. Lavoie; D. N. Assanis, Combust. Sci. Technol. 179 (9) (2007) 2039-2063.
8. Y. Shi; H.-W. Ge; R. D. Reitz, Computational optimization of internal combustion engines, Springer, 2011, p.^pp. 89.
9. L. Liang; C. V. Naik; K. Puduppakkam; C. Wang; A. Modak; E. Meeks; H.-W. Ge; R. D. Reitz; C. Rutland, in: SAE Technical Paper: 2010-01-0178, 2010, 2010.

10. J. Andrae; D. Johansson; P. Björnbom; P. Risberg; G. Kalghatgi, *Combust. Flame* 140 (4) (2005) 267-286.
11. F. Buda; R. Bounaceur; V. Warth; P. Glaude; R. Fournet, *Combust. Flame* 142 (1-2)) 170-186.
12. C. Callahan; T. Held; F. Dryer; R. Minetti; M. Ribaucour; L. Sochet; T. Faravelli; P. Gaffuri; E. Rani, *Proc. Combust. Inst.* 26 (1996) 739-746.
13. M. Chaos; A. Kazakov; Z. Zhao; F. L. Dryer, *International Journal of Chemical Kinetics* 39 (7) (2007) 399-414.
14. S. Tanaka; F. Ayala; J. C. Keck, *Combust. Flame* 133 (4) (2003) 467-481.
15. Y. Ra; R. D. Reitz, *Combust. Flame* 155 (4) (2008) 713-738.
16. C. Huang; X. Lu; Z. Huang, *Energy & Fuels* 22 (2) (2008) 935-944.
17. T. M. Foong. On the Autoignition of Ethanol/Gasline Blends in Spark-Ignition Engines. Ph.D thesis , University of Melbourne, Department of Mechanical Engineering, 2013.
18. J. B. Heywood, *Internal combustion engine fundamentals*, McGraw-hill New York, 1988, p.^235.
19. B. Lewis; G. Von Elbe, *Combustion, Flames and Explosions of Gases*. New York: Academic Press, 1951, pp.^150-160.
20. P. Dimopoulos; C. Rechsteiner; P. Soltic; C. Laemmle; K. Boulouchos, *Int. J. Hydrogen Energy* 32 (14) (2007) 3073-3083.
21. Y. Aoyagi; T. Kamimoto; Y. Matsui; S. Matsuoka, in: *SAE Technical Paper: #1980-800254*, 1980.
22. K. Akihama; Y. Takatori; K. Inagaki; S. Sasaki; A. M. Dean, in: *SAE Technical Paper #2001-01-0655*, 2001.
23. H. Ogawa; T. Li; N. Miyamoto, *International Journal of Engine Research* 8 (4) (2007) 365-378.
24. A. Bertola; R. Li; K. Boulouchos, in: *SAE Technical Paper #2003-01-3146*, 2003.
25. M. Metghalchi; J. C. Keck, *Combust. Flame* 48 (1982) 191-210.
26. T. W. Ryan; S. S. Lestz, in: *SAE Technical Paper: #800103*, 1980.

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27. D. B. Rhodes; J. C. Keck, in: SAE Technical Paper: # 850047, 1985.

28. C. Fuller; P. Gokulakrishnan; M. Klassen; S. Adusumilli; Y. Kochar; D. Bloomer; J. Seitzman; H. H. Kim; S. H. Won; F. Dryer in: *Effects of vitiation and pressure on laminar flame speeds of n-decane*, AIAA 50th Aerospace Science Meeting, 2012; 2012.

29. C. Endouard; F. Halter; C. Chauveau; F. Foucher, Combust. Sci. Technol. 188 (4-5) (2016) 516-528.

30. J. Martz; R. Middleton; G. Lavoie; A. Babajimopoulos; D. Assanis, Combust. Flame 158 (6) (2011) 1089-1096.

31. S. Marshall; S. Taylor; C. Stone; T. Davies; R. Cracknell, Combust. Flame 158 (10) (2011) 1920-1932.

32. D. Bradley; M. Lawes; M. Mansour, Combust. Flame 156 (7) (2009) 1462-1470.

33. S. Park; S. H. Chung; T. Lu; S. M. Sarathy, Energy Fuels 2015, 29, 7584–7594.

34. K. Nakata; S. Utsumi; A. Ota; K. Kawatake; T. Kawai; T. Tsunooka, in: SAE Technical Paper, 2006-01-3380, 2006.

35. C. E. Wyman; N. D. Hinman, Applied Biochemistry and Biotechnology 24 (1) (1990) 735-753.

36. A. Holley; Y. Dong; M. Andac; F. Egolfopoulos, Combust. Flame 144 (3) (2006) 448-460.

37. D. Bradley; M. Lawes; M. Mansour, Combust. Flame 158 (1) (2011) 123-138.

38. D. Bradley; P. Gaskell; X. Gu; M. Lawes; M. Scott, Combust. Flame 115 (4) (1998) 515-538.

39. D. Bradley; M. Lawes; M. Mansour, Proc. Combust. Inst 33 (1) (2011) 1269-1275.

40. M. Brusstar; M. Stuhldreher; D. Swain; W. Pidgeon, in: SAE Technical Paper 2002-01-2743, 2002.

41. M. N. Nabi; H. Ogawa; N. Miyamoto, in: SAE Technical Paper: 2002-01-2853, 2002.

42. R. J. Kee; J. F. Grcar; M. Smooke; J. Miller; E. Meeks, Sandia National Laboratories Report (1985).

43. O. A. Manna; M. S. Mansour; W. L. Roberts; S. H. Chung, Combust. Sci. Technol. 188 (4-5) (2016) 692-706.

44. D. Bradley; R. Hicks; M. Lawes; C. Sheppard; R. Woolley, Combust. Flame 115 (1) (1998) 126-144.
45. S. Chung; C. Law, Combust. Flame 55 (1) (1984) 123-125.
46. S. Chung; C. Law, Combust. Flame 72 (3) (1988) 325-336.
47. M. Matalon; B. Matkowsky, Journal of Fluid Mechanics 124 (1982) 239-259.
48. P. Pelce; P. Clavin, Journal of Fluid Mechanics 124 (1982) 219-237.
49. P. Clavin; F. Williams, Journal of fluid mechanics 116 (1982) 251-282.
50. P. Clavin, Progress in Energy and Combustion Science 11 (1) (1985) 1-59.
51. A. Kelley; C. Law, Combust. Flame 156 (9) (2009) 1844-1851.
52. Z. Chen, Combust. Flame 158 (2) (2011) 291-300.
53. C. Morely, in: *Gaseq chemical equilibrium program*, G. c. e. program, (Ed.).
54. A. E. Lutz; F. M. Rupley; R. J. Kee; W. Reynolds; E. Meeks, Reaction Design Inc 6500 (1998) .
55. N. Morgan; A. Smallbone; A. Bhave; M. Kraft; R. Cracknell; G. Kalghatgi, Combust. Flame 157 (6) (2010) 1122-1131.
56. D. Bradley; C. Sheppard; I. Suardjaja; R. Woolley, Combust. Flame 138 (1) (2004) 55-77.
57. D. Bradley; P. Gaskell; X. Gu, Combust. Flame 104 (1) (1996) 176-198.
58. P. N. Brown; G. D. Byrne; A. C. Hindmarsh, SIAM journal on scientific and statistical computing 10 (5) (1989) 1038-1051.
59. D. R. Dowdy; D. B. Smith; S. C. Taylor; A. Williams, Proc. Combust. Inst. 23 (1991) 325-332.
60. L.-K. Tseng; M. Ismail; G. Faeth, Combust. Flame 95 (4) (1993) 410-426.

61. K. Aung; M. Hassan; G. Faeth, *Combust. Flame* 109 (1) (1997) 1-24.
62. X. J. Gu; M. Z. Haq; M. Lawes; R. Woolley, *Combust. Flame* 121 (1) (2000) 41-58.
63. Z. Chen. Studies on the initiation, propagation, and extinction of premixed flames. Ph.D thesis, Princeton University, 2009.
64. M. Ghazikhani; M. E. Feyz; A. Joharchi, *Applied Thermal Engineering* 30 (13) (2010) 1711-1718.
65. S. Davis; C. Law, *Combust. Sci. Technol.* 140 (1-6) (1998) 427-449.
66. C. K. Law, *Combustion physics*, Cambridge University Press, 2006, p. 172.
67. J. Natarajan. Experimental and numerical investigation of laminar flame speeds of H₂/CO/CO₂/N₂ mixtures. Ph.D thesis, Georgia Institute of Technology, 2008.
68. P.A. Glaude; R. Fournet; R. Bounaceur; M. Molière, *Fuel Processing Technology* 91 (2) (2010) 229-235.
69. M.O. El-Faroug; F. Yan; M. Luo; R. Fifi Turkson, *Energies* 9 (12) (2016) 984.
70. F. Wu; W. Liang; Z. Chen; Y. Ju; C. K. Law, *Proc. Combust. Inst* (2014), 32, 663-670.
71. J. Santner; F. M. Haas; Y. Ju; F. L. Dryer, *Combust. Flame* 161 (1) (2014) 147-153.
72. E. Varea; J. Beeckmann; H. Pitsch; Z. Chen; B. Renou, *Proc. Combust. Inst* (2014), 35, 711-719.
73. Z. Chen; Y. Ju, *Combustion Theory and Modelling* 11 (3) (2007) 427-453.
74. Z. Chen; M. P. Burke; Y. Ju, *Proc. Combust. Inst* 32 (1) (2009) 1253-1260.
75. A. P. Kelley; G. Jomaas; C. K. Law, *Combust. Flame* 156 (5) (2009) 1006-1013.
76. Z. Chen; M. P. Burke; Y. Ju, *Combustion Theory and Modelling* 13 (2) (2009) 343-364.
77. M. P. Burke; Z. Chen; Y. Ju; F. L. Dryer, *Combust. Flame* 156 (4) (2009) 771-779.
78. Z. Chen, *Combust. Flame* 157 (12) (2010) 2267-2276.

79. J. Jayachandran; R. Zhao; F. N. Egolfopoulos, *Combust. Flame* 161 (9) (2014) 2305-2316.
80. M. Mehl; W. J. Pitz; C. K. Westbrook; H. J. Curran, *Proc. Combust. Inst* 33 (1) (2011) 193-200.
81. J. G. Stark; H. G. Wallace; M. McGlashan, *Chemistry data book*, Murray London, 1982, pp. 35-44.
82. B. E. Short, *Engineering thermodynamics*, Harper, 1953, p. 55.
83. I. Fells; A. Rutherford, *Combust. Flame* 13 (2) (1969) 130-138.
84. M. Haniff; A. Melvin; D. Smith; A. Williams, *Journal of the Institute of Energy* 62 (453) (1989) 229-236.
85. R. Stone; A. Clarke; P. Beckwith, *Combust. Flame* 114 (3) (1998) 546-555.
86. D. L. Oostendorp; H. Levinsky, *Journal of the Institute of Energy* 63 (1990) 160-6.
87. Z. Zhao; A. Kazakov; J. Li; F. L. Dryer, *Combust. Sci. Technol.* 176 (10) (2004) 1705-1723.
88. Y. N. Kochar. Laminar flame speed and stretch sensitivity of hydrocarbon fuels at high preheat, pressure and vitiation. Ph.D thesis, Georgia Institute of Technology, 2014.
89. J. B. Martz, Simulation and model development for auto-ignition and reaction front propagation in low-temperature high-pressure lean-burn engines. Ph.D thesis The University of Michigan, 2010.
90. S. Röpke; G. Schweimer; T. Strauss, in: *SAE Technical Paper #950213*, 1995.
91. Poinot, T., Veynante, D., *Theoretical and Numerical Combustion*, Second Ed., RT Edwards (2005) p. 102-120.
92. Ö. L. Gülder, *Proc. Combust. Inst* (2014), 19, 275-281.
93. G. T. Kalghatgi; D. Bradley, *International Journal of Engine Research* 13 (4) (2012) 399-414.
94. F. Halter; F. Foucher; L. Landry; C. Mounaïm-Rousselle, *Combust. Sci. Technol.* 181 (6) (2009) 813-827.
95. C. Prathap; A. Ray; M. Ravi, *Combust. Flame* 155 (1) (2008) 145-160.

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Figures

Fig. 1. Schlieren photographs of slightly rich ($\phi = 1.1$) flames of F-C, TPRF fuels at $P_0 = 0.1$ MPa (first and second columns), and TE60 and FE60 fuels at $P_0 = 0.6$ MPa (third and fourth columns) at various EGR ratios x_r , when the flame reaches about $R_f = 45$ mm.

Fig. 2. Variations of S_b with R_f for slightly rich ($\phi = 1.1$) mixture of TPRF (a) and TE60 (b) at $P_0 = 0.1$ and 0.6 MPa and $T_0 = 358$ K with/without EGR.

Fig. 3. Variations of S_b with R_f for slightly rich ($\phi = 1.1$) TPRF/ethanol blends at $P_0 = 0.6$ MPa and $T_0 = 358$ K.

Fig. 4. Variations of S_b with flame stretch rate, κ for slightly rich ($\phi = 1.1$) mixture of F-C (a) and TE60 (b) at $P_0 = 0.1$ and 0.6 MPa with/without EGR.

Fig. 5. Variations of S_b with flame stretch rate, κ for slightly rich ($\phi = 1.1$) F-C/ethanol blends at $P_0 = 0.6$ MPa at $T_0 = 358$ K.

Fig. 6. Variations of S_u^0 with ϕ for E, F-C, FE85 and FE60 flames at $T_0 = 358$ K and $P_0 = 0.1$ MPa.

Fig. 7. Variations of S_u^o with ϕ for E, F-C, FE85 and FE60 flames at $T_0=358$ K and $P_0=0.6$ MPa.

Fig. 8. Variations of S_u^o with ϕ for E, TPRF, TE85 and TE60 flames at $T_0=358$ K and $P_0=0.1$ MPa.

Fig. 9. Variations of S_u^o with ϕ for E, TPRF, TE85 and TE60 flames at $T_0 = 358$ K and $P_0 = 0.6$ MPa

Fig. 10. Variations of S_u^o with ϕ for TPRF and F-C flames with real and synthetic EGR ($x_r = 0.1$) at $T_0 = 358$ K and $P_0 = 0.1$ MPa.

Fig. 11. Variations of S_u^o with ϕ for TPRF and F-C flames with real EGR ($x_r = 0.1$) at $T_0 = 358$ K and $P_0 = 0.6$ MPa

Fig. 12. Variations of S_u^o with various volumetric fractions of ethanol for F-C and TPRF flames at $T_0 = 358$ K and initial pressures of 0.1 and 0.6 MPa.

Fig. 13. Influences of x_r on S_u^o for slightly rich ($\phi = 1.1$) (a) TPRF and TE60, (b) F-C and FE60 flames at $T_0 = 358$ K and $P_0 = 0.1$ and 0.6 MPa.

Fig. 14. Variations of $S_u^o/S_{u,datum}^o$ for TE60/air flames with (a) P/P_{datum} at $T_{datum} = 358$ K.
(b) T/T_{datum} at $P_{datum} = 0.2$ MPa.

Fig. 15. Temporal evolution of the dynamic pressure during the flame propagation.

Fig. 16. Variations of the present values of L_b at $T_0 = 358$ K and initial pressures of 0.1 and 0.6 MPa with ϕ for F-C and its developed surrogate TPRF with and without real exhaust residuals.

Fig. 17. Variations of the present values of L_b at $T_0 = 358$ K and initial pressures of 0.1 and 0.6 MPa with (a) x_r for slightly rich ($\phi=1.1$) TE60/air mixture and (b) ethanol (vol %) for slightly rich ($\phi=1.1$) TPRF/air mixture.

Tables

Table 1. Test matrix of fuel blends in terms of volume percentage.

Fuel Index	<i>FACE-C</i> [% vol]	<i>TPRF</i> [% vol]	Ethanol [% vol]	Symbols
F-C	100	0	0	■
TPRF	0	100	0	□
E	0	0	100	○
FE10	90	0	10	X
FE30	70	0	30	▲
FE45	55	0	45	►
FE60	40	0	60	▼
FE85	15	0	85	◄
TE10	0	90	10	◇
TE30	0	70	30	◆
TE45	0	55	45	*
TE60	0	40	60	+
TE85	0	15	85	●

Table. 2 Variations of detected ϕ via gas analyzer and lambda sensor with the calculated one for TPRF flames at $P_0 = 0.1$ MPa, $x_r = 0.1$ and $T_0 = 358$ k.

ϕ	ϕ (ECM Lambda)	ϕ (Horiba)
0.8	0.78	0.81
1.0	0.99	1.01
1.2	1.18	1.19