ASSESSMENT AND ANALYSIS OF TURBULENT FLAME SPEED MEASUREMENTS OF HYDROGEN-CONTAINING FUELS

A Dissertation Presented to The Academic Faculty

by

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ASSESSMENT AND ANALYSIS OF TURBULENT FLAME SPEED

MEASUREMENTS OF H2-CONTAINING FUELS

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To those whose shoulders I stand upon, to those whose shoulders I lean on, and to God to

whom I owe it all.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Flame area
AT	Instantaneous turbulent flame area
С	Progress variable
D	Mass diffusivity
Da	Damköhler number
Ka	Karlovitz number
K	Stretch rate
Kext	Extinction strain rate
Le	Lewis number
l_0	Integral length scale
l_M	Markstein length
Ма	Markstein number
Re_B	Bulk Reynolds number
Re_t	Turbulent Reynolds number
S_L	Laminar flame speed
$S_{L,0}$	Un-stretched laminar flame speed
S _{L,max}	Maximum stretched laminar flame speed
S_T	Turbulent flame speed
S _{T,GC}	Global turbulent consumption speed
S _{T,GD}	Global turbulent displacement speed
$S_{T,LC}$	Local turbulent consumption speed
$S_{T,LD}$	Local turbulent displacement speed
Т	Temperature
T_u	Temperature of unburnt gases
U_0	Mean axial velocity
u'rms	Root-mean-square turbulence fluctuations
α	Thermal diffusivity
β	Zeldovich number
γ	Heat release parameter
δ_F	Laminar flame thickness
η	Flame normal
V	Kinematic viscosity
V_t	Eddy viscosity
Σ	Flame surface density

Flow time scale
Bulk time scale
Characteristic eddy turnover time scale
Integral time scale

SUMMARY

Global efforts to reduce greenhouse gas emissions and achieve a carbon-neutral economy have spurred the exploration of integrating hydrogen into various aspects of the global energy infrastructure. This can involve incorporating hydrogen into existing power generation applications or utilizing fuels with significant hydrogen content, such as syngas. However, the introduction of hydrogen poses significant challenges due to its potential to greatly impact the combustion process, with many aspects of its behavior not yet fully understood under practical gas turbine operating conditions. This thesis aims to investigate the influence of thermodynamic, fluid mechanic, and fuel factors on the turbulent global consumption speed, $S_{T,GC}$, across different fuel types containing up to 90% hydrogen. This parameter represents the average rate of conversion of reactants to products relative to a specific iso-surface.

The presented database encompasses three distinct fuel types: H₂/CO, H₂/CO/CH₄/N₂, and H₂/CH₄, which represent fuels that are either commonly encountered in practical applications or are of interest for future applications. The latter two fuels are new to the overall Georgia Tech database of turbulent flame speed measurements which increase the amount of high pressure data (up to 20 atm), and add data at preheat temperatures up to 500 K. The addition of this data is of great importance as it allows for further exploration of thermodynamic and fuel effects on $S_{T,GC}$.

The analysis of this database reveals several key findings. Firstly, regardless of whether the unstretched laminar flame speed, $S_{L,0}$, is held constant, higher pressures lead to an increase in $S_{T,GC}$ across all fuel types. The preheat temperature is also shown to

increase $S_{T,GC}$, but when normalized by the laminar flame speed, it demonstrates a decrease. Moreover, the effects of hydrogen addition in H₂/CO and H₂/CO/CH₄/N₂ fuel blends are more pronounced compared to those in H₂/CH₄ fuels. Building upon prior studies that link these observations to mixture stretch sensitivity, the database is analyzed within the framework of a quasi-steady leading points concept model. In this framework, the maximum stretched laminar flame speed, $S_{L,max}$, serves as the normalizing parameter. This approach proves effective for the H₂/CO fuels discussed in this work, as it captures fuel effects at a fixed pressure and preheat temperature. However, a notable limitation arises in its inability to account for systematic differences in pressure and preheat temperature, indicating the need for a second correlating parameter.

To identify this second parameter, a systematic investigation of three additional dimensionless numbers, namely the turbulent Reynolds number, Re_t , time scale ratio, and acceleration ratio, is presented. Each of these numbers represents a different physical phenomenon that could potentially account for the observed variation in the data reported. The addition of Re_t was considered in prior work; however, we identify that is insufficient as an appropriate scaling number due to its inconsistent correlation with preheat temperature. The acceleration ratio was introduced as a novel means of attempting to capture the ability of a flame to accelerate relative to the flow field. Like the Reynolds number, this approach showed limited ability to capture both pressure and preheat temperature effects; nevertheless, it does offer a new way to think about turbulence-flame interactions. Ultimately, the time scale ratio emerges as the optimal second correlating parameter due to its lesser degree of scatter compared to the acceleration ratio. This finding is significant, as it aligns with prior analyses that incorporated the time scale ratio to

quantify non-quasi-steady chemistry effects at the leading point and demonstrates its promise as an appropriate scaling approach across a wide variety of conditions.

CHAPTER 1. INTRODUCTION

1.1 Motivation

By the year 2050, the Net Zero Coalition formed by the United Nations has set a target of zero carbon emissions globally which necessitates at least a 40% reduction in emissions by 2030 [1]. To achieve such an ambitious target, environmental policy has become increasingly stringent to limit the carbon footprint and decrease greenhouse gas emissions especially from energy production. Combustion currently serves as the primary means of generating energy in both industrial and transportation applications with more than 50% being driven by natural gas and coal combustion [2].

One promising innovation has been the consideration of increased use of hydrogen in the combustion process. Hydrogen addition provides myriad benefits to the combustion process all while decreasing the CO₂ produced therefrom. With much of the energy generation infrastructure centered around coal and natural gas there is a need to consider means by which hydrogen is integrated. The details of this integration are beyond the overall scope of this work; however, a few key considerations are described below.

The sourcing of hydrogen plays a role in how carbon-neutral it is. When hydrogen is produced through processes that do not produce greenhouse gases, it is called green hydrogen. In contrast, when hydrogen is processed using steam reformation of methane, a that produces CO_2 , it is called blue hydrogen. There are other "colors" of hydrogen that relate to how it is sourced; nevertheless, this suggests that even though hydrogen addition decreases CO_2 emitted during the combustion process, if the hydrogen is not sourced

properly, it could potentially lead to increased greenhouse gas emission across the entire process.

Another consideration is the actual process of burning hydrogen in combustors that are currently outfit for another fuel. Hydrogen is known to significantly alter the combustion process by expanding flammability limits, increasing the propensity for flashback, and increasing the susceptibility to combustion instabilities [3, 4]. Hydrogen, therefore, serves as a useful additive for fuels with poor lean flame stability. However, when introduced to a combustor designed for natural gas, the addition of hydrogen can cause large changes in where the flame stabilizes, and how it distributes itself inside of the engine potentially damaging engine hardware. Furthermore, in integrated gasification combined cycle (IGCC) gas turbines where coal, and ultimately syngas, serves as the fuel, large variations in hydrogen content are possible depending on the coal feedstock [5]. The large variation in hydrogen content can substantially change combustion performance motivating the need to better understand its impact on the combustion to enable effective combustor design [6].

Many practical combustion applications involve some degree of turbulence in the flowfield which can interact with the combustion process significantly. Turbulence enhances mixing due to the interaction of the superimposed time, length, and velocity scales within the flow field. The enhanced mixing of reactants changes how the flame propagates which is typically quantified by the turbulent flame speed, S_T . S_T plays a critical role in the design of combustors because it impacts flame stability. During stable operation, a flame will stabilize inside of a combustor and distribute itself some length therein. However, if the local incoming flow velocity becomes less than that of the flame speed,

the flame will propagate upstream potentially leading to flashback. Alternatively, if the local incoming flow velocity exceeds the flame speed, the flame may blowoff. In either case, critical engine hardware is exposed to extreme temperatures and combustor performance decreases significantly. S_T also impacts flame shape, or the spatial distribution of the flame within the combustor. Understanding flame shape is important as it influences the thermal loading on the combustor walls which is correlated with combustor lifetime, and how the flame will interact with acoustic disturbances therein. The presence of hydrogen has been well documented to influence both flame shape and stability [4, 7], especially in turbulent flames where the stretch sensitivity is an important consideration.

With an understanding of the importance of hydrogen addition and S_T , the rest of this chapter presents a brief overview of key relevant topics pertaining to this research, a review of existing literature pertaining thereto, and an overview of major research questions along with the scope and organization of this thesis.

1.2 Premixed Turbulent Combustion

This section details the major theoretical concepts applied in this thesis. Beginning with an overview of the fundamentals of how turbulence interacts with flames, we follow this discussion with a fundamental formulation of S_T . Thereafter, additional detail into important nuances in interpreting S_T measurements and analysis are discussed.

1.2.1 Regime Diagram

Laminar flames are typically characterized by a single length scale known as the flame thickness, δ_F , and a single velocity scale, the laminar flame speed, S_L . In laminar

flames the mixing process is driven by the diffusion of radicals into the preheat zone. In the presence of turbulence, that mixing process is further enhanced by eddies in the flow. Turbulence is also a multi-scale phenomenon meaning that there are a variety of length and velocity scales that can interact with the flame. A visualization of this interaction can be seen in the work of Aspden *et al.* who developed DNS of lean premixed hydrogen flames as shown in Figure 1 below [8].



Figure 1. Two dimensional slices of 3-dimensional DNS data of lean premixed hydrogen flames. Adapted from Ref. [8].

Here the degree of turbulence-flame interaction is quantified by the Karlovitz number, *Ka*, and increases from left to right for the density, burning rate and temperature fields. Of note is the substantially change increasing turbulence has on the flame and combustion process. To better characterize these interactions, Borghi *et al.* developed a regime diagram that was later modified by Peters [9] as seen in Figure 2.



Figure 2. Borghi-Peters Diagram

The Borghi-Peters diagram characterizes the expected phenomenological interactions of the combustion process by comparing a normalized turbulence intensity, $u'_{rms}/S_{L,0}$, and a normalized length scale ratio, l_0/δ_F . In this diagram, there are five zones of interest. The laminar flame regime is defined where Re_t is at most one. Here both the turbulence intensity and length scale ratio are too small for turbulence to significantly modify the flame. In the wrinkled flame regime, the turbulence intensity is less than one; however, the length scales of turbulence can disturb the flame front. Despite the length scale interaction, laminar flame propagation still dominates in this regime. In the corrugated flamelet regime, the Karlovitz number defined in Equation 1 below still remains less than one.

$$Ka_{\eta} = \left[\left(\frac{u'}{S_L} \right)^3 / \frac{\ell_0}{\delta_f} \right]^{\frac{1}{2}}$$
(1)

Under these conditions, the thickness of the reaction-diffusion zone is less than the Kolmogorov scale allowing for perturbations in the flame; however, the overall flame structure exhibits limited changes. The thin reaction zone characterized by Ka_{η} between 1 and 100. Here, the Kolmogorov scale can interact increasingly with the reaction-diffusion zone, in some cases this produces "thickened flamelets" where the convective-diffusive zone of the flame is enlarged without significant modification to the diffusion-reaction zone [10]. Beyond Karlovitz numbers of 100, the flame is impacted by small scale turbulence to an even larger degree. This can lead to local quenching and/or reaction zones that better resemble well-stirred reactors. The data this thesis discusses is distributed across all but the wrinkled and laminar flame regimes.

It is important to note that the flame thickness can be defined based on the temperature gradient across the flame, i.e. "thermal" flame thickness, or based on the characteristic diffusion length scales, i.e., "diffusion" flame thickness. There are also other flame thicknesses that could be defined based on reaction rate, heat release, etc. that may be more appropriate for a given fuel. This difference is important because the original formulation by Peters uses the diffusion flame thickness[11]. While the values of these parameters are typically related by a constant, this makes a difference when looking at how other parameters are defined on the regime diagram. For instance, the Reynolds number is typically defined in Equation 2 below.

$$Re_t = \frac{u'\ell_0}{v} \tag{2}$$

However, the Peters formulation assumes that the kinematic viscosity is defined as $v = \delta_f S_{L,0}$. This nuance was reiterated in a review paper by Steinberg *et al.* noting that this could lead to significant differences in interpretations of various nondimensional parameters [12]; this is corroborated by Fillo *et al.* who estimated the uncertainty due to these definition differences could change values by up to an order of magnitude [13]. Additionally, other authors have recognized the limitations of the Borghi-Peters diagram and have worked to modify it; for instance, Skiba *et al.* introduced a thickened flamelet regime into the diagram [14, 15]. The details of these modifications are outside the scope of this work but reiterate that turbulence can significantly influence the combustion process. The turbulence flame speed is one metric that is used to quantify said complex interactions.

1.2.2 Damköhler's Hypotheses

One of the initial formulations of S_T was developed by Damköhler using the model problem shown in Figure 3 below.



Figure 3. Model used to understand the turbulent consumption speed.

By applying a conservation of mass approach within the defined control volume, the turbulent flame area, A_T , propagating everywhere along at a velocity of S_L is matched to a flat flame area, A_L , propagating at the turbulent flame speed, S_T , leading to Equation 3.

$$\frac{S_T}{S_L} = \frac{A_T}{A_L} \tag{3}$$

This formulation helped form the basis for two important hypotheses in turbulent combustion. Based on these equations Damkohler developed two hypotheses. The first hypothesis suggests that the increase in the turbulent flame speed is proportional to the amount of flame surface area generation. This relationship can be further extended by assuming how each area is related to u'_{rms} and S_L , we land at the Equation 4.

$$\frac{S_T}{S_L} \approx \frac{u' + S_L}{S_L} \approx 1 + \frac{u'}{S_L} \tag{4}$$

This leads to a theoretical limit of $S_T \rightarrow u'_{rms}$ as turbulence increases; however, in the large turbulence intensity limit, this leads to Damköhler's second hypothesis where the right-hand side is replaced by following ratio of relative eddy viscosity and mass diffusivity [16] shown in Equation 5.

$$\frac{S_T}{S_L} \sim \sqrt{\nu_t / D} \tag{5}$$

The second hypothesis takes on can be observed in turbulent flame speed data qualitatively via the "bending" shown at high turbulence intensities and the corresponding square root relationship shown in the equation.

Validation of these hypothesis exists in much of the literature; however, more recent literature has suggested that the hypotheses are only true in an order of magnitude sense, or only in flow fields without a mean gradient [17-19]. Nevertheless, these approaches are foundational in understanding of the potential ways that we have attempted to quantify and describe the turbulent flame speed. In the next section, we examine the critical role that stretch plays in understanding S_T .

1.2.3 Flame Stretch Effects

Turbulent flow fields can exhibit high degrees of non-uniformity and unsteadiness. When a flame interacts with such flow fields, this can induce flame front changes that cause flow streamlines and heat/species diffusion to become misaligned leading to local alterations in the flame. The flame stretch rate is typically quantified by the expression introduced by Williams *et al.* [20] as the material derivative of the logarithm of the flame area:

$$\kappa = \frac{1}{A} \left(\frac{DA}{Dt} \right) \tag{5}$$

By applying vector calculus, this equation can be re-expressed as:

$$\kappa = \nabla_t \cdot \boldsymbol{v}_f + (\boldsymbol{v}_f \cdot \boldsymbol{n}) (\nabla \cdot \boldsymbol{n}) \tag{6}$$

This expression contains two terms, the first is called tangential strain rate which is driven by the flow field, while the second term refers to flame curvature and flame motion [21]. These two terms along with key mixture properties can lead to local extinction, local enhancement on the burning rate, or no change to the flame. Which of these occurs is typically mixture-specific, and driven by thermodiffusively stability, preferential diffusion, and the Darrius-Landau instability.

Thermodiffisuve instabilities arise because of a mismatch in relative mass and thermal diffusivities which captured by the Lewis number:

$$Le = \frac{\alpha}{D} \tag{7}$$

where α is the thermal diffusivity, and *D*, is the mass diffusivity. At unity, the Lewis number indicates that there is a balance between mass and thermal diffusion meaning that the local flame stoichiometry will be similar to that of an adiabatic flame. However, when this value is non-unity there is a local focusing/defocusing of reactants and heat which can lead to sub/super-adiabatic flame temperatures locally which will correspondingly see an alteration in the burning rate. Furthermore, a local augmentation of S_L is referred to a thermodiffusively unstable flame, while the local diminishment is thermodiffusively stable. Preferential diffusion occurs when there are some species whose mass diffusivity is much higher than others. For instance, H₂ has a mass diffusivity nearly four times higher than that of CH₄ and CO. Thus, in flames that contain these constituents, H₂ will tend to diffuse into the flame faster which could lower the equivalence ratio and lead to extinction. This is one of the mechanisms by which tip opening in Bunsen flames occurs [22].

Thus far, this discussion has focused on the phenomenology of flame stretch. However, significant work has taken place to quantify the stretch sensitivity of various flames. Through asymptotic analysis, a first order expression of the sensitivity of the laminar flame speed in the weak stretch limit was developed [20].

$$S_L = S_{L,0} - \ell_M \kappa \tag{8}$$

where ℓ_M is referred to as the Markstein length, is the sensitivity of the flame speed to stretch. The Markstein number, Ma, was similarly derived using asymptotic analysis of single step, irreversible chemistry shown in Equation 9.

$$Ma = \frac{1}{\gamma} \ln\left(\frac{1}{1-\gamma}\right) + \frac{\beta(Le-1)}{2} \left(\frac{1-\gamma}{\gamma}\right) \int_{0}^{\gamma/(1-\gamma)} \frac{\ln(1+x)}{x} dx$$
(9)

Ma is defined as the ratio of the Markstein length to the flame thickness, ℓ_M / δ_F , γ is a heat release parameter, β is the Zeldovich number, and *Le* is the Lewis number as previously defined.

Turbulent flames, however, tend to experience strong stretch effects as well. At these levels, the linear relationship defined in Equation 8 begins to fail. To model the flame speed at high stretch rates, the OPPDIFF package in CHEMKIN can be used to simulate these conditions by modelling an opposed diffusion flame. An example of these measurements can be seen Figure 4.



Figure 4. Stretch sensitivity calculations of H₂/CO fuel blends and CH₄ for a 1 atm, 300 K flame with stoichiometry to maintain $S_{L,\theta}$ values of 34 cm/s. Adapted from Ref. [23].

A key observation in Figure 4 is the increase of the laminar flame speed with increasing strain rate which is a result of the fuel having a negative Markstein length. Thus, areas experiencing positive strain in the flow will tend to have higher local laminar flame speeds; and in some cases, this can be the maximum stretched flame speed, $S_{L,max}$. Said flame speed is often associated with the leading points on the flame. Leading points can be

thought of as the positively curved points on the turbulent flame front that propagate furthest into the reactants as illustrated in Figure 5.



Figure 5. Example illustration of a leading point.

The concept of leading points is derived using Kolmogorov-Petrovsky-Piskunov (KPP) theory. This is then used to relate the turbulent flame speed of a statistically 1D flame residing in a prescribed statistically stationary turbulent flow field to the average reaction rate at the leading edge of the flame brush [24]. As a result, some authors have hypothesized that the dynamics of these points – specifically, their ability to "pull" the flame – as the controlling mechanism of the overall propagation velocity of the turbulent flame [25]. Thus, fuel/air mixtures with negative Markstein numbers will have enhanced laminar flame speeds at the positively curved leading points, resulting in larger displacement speeds.

1.2.4 Turbulent Flame Speed Definitions

There are four primary definitions of the turbulent flame speed as suggested at the International Workshop of Premixed Flames by Gouldin and Cheng [26]. The definitions are split between local and global, and consumption and displacement. Local definitions refer to a flame speed at each location across the flame, while global definitions average over the entire flame. Hence, local definitions tend to be presented as distributions unless the specific reference point is specified. Displacement definitions are related to the kinematic velocity at which the flame is propagating while consumption definitions are how fast a flame is consuming reactants.

The nuances in definitions are importance for a few key reasons. First, different measurement techniques provide different information lending each definition to a specific type of measurement. A clear example of this is using line-of-sight chemiluminescence to deduce a local measurement. In the case of $S_{T,GC}$ multiple measurement techniques are available. Line-of-sight measurements such chemiluminescence (as discussed above) and Schlieren [27] have been used to capture the turbulent global consumption speed. Alternatively, planar measurements such as laser tomography [28], Mie scattering [29] and OH-PLIF [30] have been used by other authors. Both techniques have their advantages and disadvantages. For instance, line-of-sight measurements cannot provide the instantaneous flame position or capture 3D artifacts such pockets of burning reactants within the reaction zone. On the other hand, planar measurements typically underestimate the local flame surface density [31]. Despite these differences, various authors report consistent qualitative trends in $S_{T,GC}$ to turbulence intensity, and to pressure when only pressure is being changed (except in Ref. 71).

Secondly, different experimental configurations have more appropriate definitions. For instance, in flowing systems, the bulk flow velocity is a key consideration, as opposed to those without one such as a spherical bomb. Lastly, when making comparison between turbulent flame speed definitions quantitative agreement is rarely guaranteed, which is commonly associated with progress variable definition which varies between configurations. Each of these factors are important in properly interpreting turbulent flame speed data, and the rest of this section provides a brief overview of the current definitions and its current applications.

The turbulent local displacement speed is the velocity at which a given point on the flame propagates into the reactants,

$$S_{T,LD} = (\overrightarrow{v_F} - \overrightarrow{v_R}) \cdot \vec{n} \tag{10}$$

where $\overrightarrow{v_F}$, $\overrightarrow{v_R}$, and \overrightarrow{n} refer to the flame front velocity, the reactant flow velocity, and the normal along the flame front. This measurement is commonly seen in DNS measurements computationally [32], and in V-flame and LSB configurations using either PLIF [4] or Mie Scattering imaging [33]. The turbulent global consumption speed is the average speed a flame propagates into reactants and has varying definitions depending on the system allowing it to be applied to both V-flame and spherical bomb configurations.

Local turbulent consumptions speeds are a measure of how much a given flame element can consume reactants and is typically defined as in Equation 11.

$$S_{T,LC} = S_{L,0} I_0 \int \Sigma d\eta \tag{11}$$

where $S_{L,0}$, I_0 , Σ , η indicate the unstretched laminar flame speed, stretch factor, flame surface density, and flame coordinate. This definition is also most often seen in DNS applications because of the difficulty in measuring it experimentally. Its global counterpart - turbulent global consumption speed -- is the average conversion of reactants to products across the entire flame and is often measured on Bunsen-flame configurations.

1.3 Literature Review

The turbulent flame speed has been investigated in a variety of computational, experimental, and theoretical work much of which has been summarized in various review papers [25, 34]. The goal of this literature review is examining existing research that focused on parametric effects on S_T , and the models that were developed therefrom. These parametric effects can be divided into three major classes: fluid mechanic effects, fuel effects, and thermodynamic effects each of which will get its own section. The empirical models in the literature are numerous but center on a few paradigms which will also be discussed.

1.3.1 Fluid Mechanic Effects

Fluid mechanic effects are those that related to how changes in turbulence intensity, inlet velocity, U_{θ} (in flowing systems), and turbulent length scales influence S_T . These effects are well quantified with increased turbulence leading to an increase in S_T . Turbulence is typically imparted into experimental setups by fans (for spherical bombs), or some degree of blockage upstream of the burner. In many facilities, the blockage plates directly couple U_{θ} and u'_{rms} [27, 35], this is important to recognize when interpreting results from these facilities as they involve a bulk flow component inherently. More recent work involves facilities that decouple these two key velocity measurements allowing for a better understanding of each individual effect [36]. In either case, the "bending effect" is observed. The initial increase the turbulent flame speed with turbulence is thought to be a direct reflection of an associated increase of the flame area as recognized in Equation 4.
However, at higher u'_{rms} the increase in flame area is thought to lessen due to local quenching and flame merging [37-40]. The quenching is directly observed in data from Bradley *et al.* where the quench is directly demarcated in Figure 6.



Figure 6. Turbulent global displacement flame speed measurements developed by Bradley demonstrating quench in spherical bomb data. [41].

Additionally, there are specific considerations of the burner diameter effect in systems where the flow may be tangential to the flame surface which are understood to be nontrivial [42]. For instance, Filatyev *et al.* when building a model included both a normalized inlet velocity, $U_0/S_{L,0}$, and normalized burner diameter, D/l_0 , as a part of the analysis [43]. More recent work also suggests that the burner diameter may have an impact on how the Darrius-Landau instability is able to manifest in turbulent burner stabilized flames [44].

1.3.2 Fuel Effects

The next class of effects are fuel effects which relate to how fuel composition and equivalence ratio influence S_T . These effects influence stretch sensitivity, and preferential thermal diffusion effects, which are critical to understand in turbulent environments. There is a general agreement on the impact of equivalence ratio, and it matches, at least qualitatively, that of the laminar flame speed. Similarly fuel composition effects of S_T have been studied at large with focuses on H₂/CH₄ [45-48], H₂/CO[23, 36, 49-51], effects of diluents, effects of Coal Dust addition [52], heavy hydrocarbon fuels (lean and rich) [53], alternative Jet Fuels [54], and more recently ammonia [55]. There have been a variety of attempts to capture these so-called "fuel effects" based on Lewis number scalings; specifically, Liu normalized the Lewis number and was able to get a reasonable collapse of data [56]. Chakraborty introduced the Markstein diffusion concept and was able to apply that to complex heavy HC fuels with reasonable success [57]. And, Venkateswaran et al. was able to collapse H₂/CO fuel blends at different equivalence ratios, and constant laminar flame speeds for a given pressure by normalizing by $S_{L,max}$, the velocity of the furthest propagating point into reactants of a negative Markstein length fuel [36].

This velocity was derived based on the leading points concept, which was introduced by Zeldovich and expanded on by various other groups as reviewed in Ref. [25]. Leading points can be defined as the positively curved point on the flame that propagates furthest into the reactants. The leading points concept has been applied to a variety of datasets and has shown promise in capturing fuel effects for hydrogen-containing and hydrocarbon fuels [58, 59], specifically by normalization of S_T by the leading point velocity. Despite the varying methodologies that have shown some success for certain

researchers, there remains a need to address two key aspects. Firstly, there is a need to enhance the understanding of the underlying physical mechanisms responsible for the sensitivities to fuel effects. Secondly, it is important to continue conducting measurements across a range of fuel blends. Hydrogen-containing mixtures are of particular interest due to their practical significance, and they raise intriguing questions about the interactions between turbulence and chemistry, especially when the fuels exhibit significantly different diffusivities.

1.3.3 Thermodynamic Effects

Lastly, are thermodynamic effects that are related to pressure and preheat temperature effects both of which influence both the chemistry and fluid mechanic phenomena that take place in a practical gas turbine engine. For instance, pressure increases the Reynolds number which energizes small scall turbulence. At the same time, the flame thickness decreases allowing smaller scales to interact with a flame, and the flame speed decreases leading to less smoothing of the flame through kinematic restoration mechanisms. Together, this can contribute to an increase in the flame area and ultimately change the turbulent flame speed.

As it specifically pertains to the turbulent flame speed, however, there are very few studies that directly address the sensitivity of the turbulent flame speed to preheat temperature effects. For instance, Won *et al.* measure the turbulent flame speed of n-heptane, a heavy hydrocarbon, with the goal of understanding low temperature chemistry effects. They note that there is a non-trivial impact on the turbulent flame speed as the flame shortens significantly as the preheat temperature is increased from 400 K to 700 K.

However, their primary goal was to investigate the impact of low temperature ignition effects [60]. Furthermore, Lin *et al.* examine the sensitivity of the turbulent flame speed of pure hydrogen mixtures where they found S_T to scale as $(T/T_{ref})^{0.5}$ but for syngas mixtures noted a greater sensitivity of $(T/T_{ref})^{1.34}$ [61]. Finally, Daniele et al built a correlation with their turbulent flame speed and introduce a temperature correction factor (T/T_{ref}) here T_{ref} is 1 K as opposed to 298 K as in the work at Won, and noticed a slight decrease in spread of the data, but it was not as marked as the pressure correction [62]. These studies that preheat temperature effects are nontrivial, exhibit an additional dependence on the fuel type, and should be studied in greater detail to infer the physical mechanisms driving its impact more directly on S_T .

Like preheat temperature effects, pressure impacts both chemistry and fluid mechanic parameters, and exerts its influence on laminar flame speed, stretch sensitivity, and flame thickness (thereby, influencing growth rates of the Darrius-Landau instability). Furthermore, the pressure effect has proven to be one of the most ambiguous effects to interpret. Without proper specification in interpreting these pressure sensitivity results, we note that it is important to consider what is being compared (i.e., the absolute value of S_T itself, or a normalized value; $S_{L,0}$ is commonly used, which itself is a function of pressure), as well as what is being held constant during the comparison of what is being held constant while pressure is changed (e.g. u'_{rms} , $u'_{rms}/S_{L,0}$, turbulent Reynolds number, etc.), drawing conclusions about the effect of pressure can be erroneous or misleading. This may be the reason that reports in the literature show an increase, decrease, or no change in the turbulent flame speed. For example, Kobayashi *et al.* showed a significant increase in S_T/S_L with increasing pressure for a given $u'rms/S_{L,0}$ while S_T itself was independent of pressure [63].

On the other hand, various authors have found that S_T and its associated normalized values increase with pressure [23, 36]. Furthermore, Liu *et al.* found that at constant turbulent Re (by varying pressure, integral length scale and turbulence intensity) S_T decreases with increasing pressure [63]. Thus, at this point, it is not clear what the general pressure scaling is for the turbulent flame speed.

1.3.4 Turbulent Flame Speed Modelling

Modelling the sensitivity of the turbulent flame speed takes on a variety of approaches ranging from theoretical [11, 64, 65] to purely empirical [27] all of which aim to develop a physics-based understanding of how different parameters affect S_T . Theoretical approaches tend to provide good intuition on expected trends and provide a solid basis for understanding a relationship, but are often limited in their generalizability because of the inherent limitations in how they are derived. This can be seen in Damköhler's first/second hypothesis which have been shown to have limited applicability for flow fields that have a mean gradient [18, 19]. On the other end of the spectrum of approaches are those that are developed from measurements. These models tend to take the form,

$$\frac{S_T}{S_L} = f\left(\frac{u'}{S_L}, x_i, \dots\right) \text{ where } i \in [1, N]$$
(12)

where x_i can be up to N nondimensional parameters. For instance, in attempting to understand the pressure effect, Kobayashi added a pressure correction term p/p_0 to methane-air data [27] yielding a correlation of the form

$$\frac{S_T}{S_L} = C \left[\left(\frac{u'}{S_L} \right) \left(\frac{p}{p_o} \right) \right]^a \tag{13}$$

with the primary goal being to capture the effect of pressure on methane flame at pressures up to 3.0 MPa [27, 66].

Muppala *et al.*, on the other hand, used measurements of methane, ethylene, and propane at various pressures and built a correlation of the form:

$$\frac{S_T}{S_L} = 1 + \frac{C}{Le} Re_t^a \left(\frac{u'}{S_L}\right)^b \left(\frac{p}{p_o}\right)^c \tag{14}$$

Given the existence of a variety of models there has been an increase in identifying which correlations are the most accurate. For example, Burke *et al.* quantified the mean absolute percentage error (MAPE) across 16 different correlations for the turbulent flame speed of gaseous hydrocarbons and was able to identify five correlations that performed the best after tuning model constants [67]. This work was continued by Yousefian *et al.* who optimized a generalized correlation across different conditions across the five correlations [68]. In both cases, the error was minimized to around 15-20%. This suggests that these methods have a limited predictive capability. Although these correlations share common terms, the inclusion of different data/terms in the equation itself will ultimately lead to different constants which prompted questions around the "generality" of turbulent flame speed models [69]. While it was concluded that existing measurements and models do not preclude generalization, the inherent limitations of this modelling approach were brough to the forefront. For instance, while these correlations are instructive in providing

a qualitative understanding of a particular variable's influence on the turbulent flame speed (e.g., the pressure is positively correlated, while the Lewis number may be inversely related), they do not necessarily provide physics-based insight.

To address with some of these challenges more recent modelling completed by Venkateswaran *et al.* combined the physics of the leading points concept into its empirical modelling. This led to a model of the form shown in Equation 15 below:

$$\frac{S_T}{S_{L,max}} = f\left(\frac{u'}{S_{L,max}}, \frac{\tau_{S_{L,max}}}{\tau_{flow}}\right)$$
(15)

This model incorporates the quasi-steadiness of the leading into the model by adding a second nondimensional parameter, the leading point time scale ratio, to capture both fuel and pressure effects. This method showed significant success for multiple datasets outside of just the dataset from which it was developed. The only limitation of said approach was the question of would it generalize to all thermodynamic effects, because the time scale ratio could easily be replaced by any other variable that scaled monotonically with pressure [58]. Thus, this approach requires further testing to identify its robustness to a broader range of conditions.

1.4 Objectives and Scope

The prior sections discussed the importance of S_T , topics central to this work, and reviewed the existing pertinent literature making it clear that a few challenges persist in understanding parametric effects and their underlying physical mechanisms as it pertains to S_T . First, there is a lack of hydrogen-methane and multi-component (more than two component) syngas S_T measurements across a large operability range. These are important to confirming or denying whether prior conclusions discovered from prior work still hold over a larger parameter space. Second, there is limited data of turbulent flame speeds that directly investigate preheat temperature effects especially for hydrogen-containing fuel blends. An understanding of preheat temperature effects is key to getting a more complete understanding of thermodynamic effects on S_T given the large amount literature examining pressure effects. Lastly, although the existing modelling approach has shown success in capturing fuel and pressure effects, it still requires validation across more fuel blends and thermodynamic conditions. Given these challenges the objective of this thesis are as follows:

- Expand the existing Georgia turbulent flame speed database with more measurements of hydrogen-containing fuel blends specifically those containing H₂/CO/CH₄/N₂ and H₂/CH₄ fuels. These fuel blends are of relevance for better understanding the burning characteristics of industrial syngases and hydrogen addition to natural gas, respectively.
- 2. Explore the entire database to evaluate the relationship of $S_{T,GC}$ with different fluid mechanic, fuel, and thermodynamic effects with the goal of understanding how this may be tied to stretch sensitivity of the mixture, and thermo-diffusive stability of the mixture.
- 3. Examine the limitations and opportunities of current or alternative modelling approaches for the turbulent flame speed and their robustness to different fuel types.

Given these objectives the rest of this thesis is organized as follows.

Chapter 2 delves into the methodology employed in analyzing the Georgia Tech database to gain a physics-based understanding of turbulent flame speed behavior. It begins by discussing the experimental work conducted, including the processing and analysis of turbulent flame speed data. Furthermore, it covers the simulation of corresponding laminar flame properties. In Chapter 3, a comprehensive analysis of the Georgia Tech database is presented. It starts with a review of the legacy data contained within the database, followed by a detailed examination of more recent datasets. Chapter 4 builds upon the preceding analysis by investigating the capability of the existing model to capture fuel and thermodynamic effects. Additionally, an alternative model that encompasses both fuel and thermodynamic effects is explored. Finally, Chapter 5 offers key conclusions and contributions derived from the research. It also suggests potential avenues for future research endeavors. By following this structure, the thesis aims to provide valuable insights and advancements in understanding turbulent flame speed, as well as pave the way for further research in the field.

CHAPTER 2. METHODOLOGY

The objective of this chapter is to offer a comprehensive overview of the methods employed for measuring and analyzing the turbulent flame speed of hydrogen-containing fuel blends. Section 2.1 presents an overview of the experimental facility utilized in the study, providing a detailed description of the setup and equipment used. Following that, Section 2.2. delves into the measurement of turbulent flame speed using chemiluminescence and outlines the specific procedures and instruments used for data collection. Thereafter, Section 2.3 focuses on the calculation of relevant flame properties necessary for the development of scaling laws in subsequent chapters. Finally, Section 2.4 analyzes potential sources of uncertainty in the measurements presented. Note this work builds off of the work of Venkateswaran [70], as such much of this chapter is repeated from that body of work with some updates based on increased capabilities.

2.1 Experimental Facility

This study focuses on measurements of the turbulent global consumption speed definition of S_T as recommended by Gouldin and Cheng [26] for a Bunsen burner configuration. This definition provides ample opportunity for comparison with work by Kobayashi [27, 35, 71], Daniele [30, 51, 72], and Zhang [59]. $S_{T,GC}$ is defined below:

$$S_{T,GC} \equiv \frac{m_R}{\rho_R \overline{A_{}}} \tag{16}$$

where m_R is the mass flow rate of the reactants, ρ_R is the density of the reactants, and $A_{<c>}$ is the averaged area of a progress variable contour of interest < c >. This parameter

captures the average rate of conversion of reactants to products across the flame. Measurement of this quantity is done using an experimental facility that features three main components: the burner, variable turbulence generator, and pressure vessel.

Figure 7 shows a schematic of the Bunsen burner used in this experiment. The nozzle is smoothly contoured with a high contraction ratio which is used to inhibit boundary layer growth. Note this figure shows only two fuels, H₂ and CO; however, the system was further updated to handle up to four fuels at a time.



Figure 7. Schematic of burner facility when H₂/CO is the fuel [36].

This geometry leads to the formation of a top hat velocity profile at the exit. To ensure proper mixing of the fuel and air, the reactant mixture is allowed to mix over a length of 2 meters. The premixed mixture then flows through ball bearings before passing through the turbulence generator and exiting the nozzle. The nozzle is surrounded by a 10micron sintered plate through which a CH₄/air mixture is passed to stabilize the main flame and limit reactant leakage across the pilot. The pilot mass flow is limited to less than 5% of the main flow to limit the impact on the measurement of $S_{T,GC}$. Fuel and pilot air are metered using sonic orifices, each of which is supplied from tanks allowing for up to four fuels in the main flow, as opposed two fuels in the prior work. The sonic orifices were calibrated using a Ritter drum-meter calibrator with an accuracy of 0.2%. Flow rates are controlled using air-loaded pressure regulators controlled by ER-3000 pressure controllers.

The airflow for the main flame is delivered from blowdown tanks that store compressed air from the main facility compressors at up 2500 psi. Another change between the prior work and the modified facility used in the current measurements is the airflow rate is metered using a Rosemount 8800 vortex flow meter after which the flow is choked before mixing with the fuel. Upon entering the burner assembly, a layer of small iron balls to minimize jetting effects from the smaller diameter reactant feed lines. The air can be preheated up to 600 K by passing the air through the main facility furnace. Furthermore, to ensure successful heating the main airlines are wrapped with heat trace and insulated with fiberglass insulation.

Figure 8 shows an image of the variable turbulence generator developed for the burner facility. By allowing independent control of nozzle velocity, and turbulence intensity this facility is different from many other flowing system burners that use blockage plates such as those used in Coppola *et al.* [73].



Figure 8. Schematic of a partially closed turbulence generator plate [36].

Two key features of the variable turbulence generator are the flow straightener plates, and the remote operability of the setup. The flow straighter plates limit the amount of swirl introduced into the flow because at high blockage ratios the flow must angle itself to pass through the plates. After passing through the turbulence generator plates, the flow impinges on the walls of the contoured nozzle. This is an important design element, as nozzles with too large of a diameter, or blockage plates with too small a diameter of the open area, allow the large-scale structure generated at the blockage plate to exit the nozzle without impinging upon the walls of the contoured nozzle. Since the aim is to achieve homogeneous turbulence with no narrowband spectral features, this is undesirable. As such, the inner diameter of the radial slots was set to 30 mm, 1.5 times larger than our largest nozzle diameter.

Measurements and characterization studies were conducted under isothermal flow conditions with burner diameters of 12 and 20 mm to achieve different ranges of length scales and assess their influence on the turbulent flow properties [74]. The range of blockage ratios possible with this setup is 69-97%, corresponding to angular slot openings from $30^{\circ}-2^{\circ}$. The 30° angular slot opening corresponds to the fully open position, where the two plates are aligned. The characterization of the facility allowed for the development of empirical relationships of the blockage ratio and turbulent flow quantities (i.e., turbulence intensity, u'_{rms} , and integral length scale, l_0) and the mean inlet velocity, U_0 .

Secondly, by using a stepper motor and optical encoder from US-Digital, the rotated angle of the plates was able to be controlled with a resolution of 0.1°. The rotated angle and corresponding normalized turbulence intensity, u'_{rms}/U_0 , is based off of flow characterization completed by Marshall *et al.* [74]. These results were validated against measurements current measurements between two different burner diameters for a CH₄/air mixture at STP and equivalence ratio of 0.9. Furthermore, all work completed on this facility remained within the ranges for which the flow characterization was completed.

Lastly, the pressure vessel shown in Figure 9 was designed to be optically accessible at pressures up to 30 atm. A co-flow is introduced along the inside of the vessel to support the pressurization and cooling of the walls within the combustion chamber.



Figure 9. Fully assembled experimental facility [70].

Further cooling is introduced in the form of a water jacket around the vessel to avoid exceeding temperatures that would damage the vessel.

During high-pressure experiments, only three quartz windows are used while the fourth is replaced by high-carbon steel blanks through which the ignition system is passed. The ignition system consists of a 1/4" diameter stainless steel tube and a 1/8" diameter copper rod that run parallel to each other 2.5" apart into the pressure vessel through the window blank. The stainless-steel tube is connected to a hydrogen tank with two inline 'normally closed' solenoid valves, while the copper rod is connected to a high-voltage 120

VAC transformer. The solenoid valves and the transformer are on the same circuit operated by a switch. When the switch is activated, a spark is generated between the copper rod and stainless-steel tube, igniting the flowing hydrogen, which subsequently ignites the pilot flame.

A cold co-flow, which is choked upstream of the pressure vessel, enters the vessel through two ports at the bottom. The co-flow serves to keep the walls of the pressure vessel cool as well as to pressurize the vessel. Like the main burner flow, the co-flow also passes through a layer of ball bearings to minimize "jetting" effects from the smaller diameter feed lines. Operation of the vessel begins with stabilizing the pilot on the burner at near atmospheric pressure. Upon pilot stability, the premixed air-fuel mixture is flowed through to achieve the desired U_0 , fuel split, and equivalence ratio, pressure, and preheat temperature before data is captured.

An important consideration during data collection is ensuring that the flame is fully anchored and closed to ensure that reactants are passing through the flame. An example of a partially anchored flame is shown in Figure 10. The lack of anchoring of the right side of the flame gives reactants a direct path to escape without being burned.



Figure 10. Partially (left side) anchored 100% CH₄ flame at 1 atm, 300 K and $U_0 = 35$ m/s.

In the cases where the flame is identified to be in either of these undesirable conditions, data is not captured. This is because the definition of the flame speed requires that on average the flame reference area be closed to prevent reactants from escaping. Without this consideration, the flame speed can be overestimated.

2.2 Flame Imaging

At the desired test condition, the data captured leverages either CH* or OH* chemiluminescence with the former being applied to mixture that contain CH₄ and high hydrogen containing fuels for H₂/CO fuels specifically, respectively. For H₂/CO fuels, a 105 mm, f/4/5, UV camera lens was used since this lens is sensitive in the visible and ultraviolet regions (~220-650 nm) and hence can capture both OH* and CH*. This is important since the OH* chemiluminescence associated with hydrogen flames emits in the

UV range. For the pure methane, H_2/CH_4 , and $H_2/CO/CH_4/N_2$ flames, lenses of varying focal lengths were utilized along with a CH* filter. The CH* filter was a bandpass filter with a center wavelength of 430 ± 2nm with a FWHM of 10 ± 2nm to capture the primary CH* emission at 431 nm.

Flame images are captured at 60 Hz and stored in the TIF format. These images are then averages across a timespan of two seconds of data. This set of images is averaged and then left/right averaged to produce a single axisymmetric image. Using chemiluminescence images provides line-of-sight integration, which is filtered by applying an inverse Abel transform, which allows visualization of the center-plane of the flame. A visualization of this processing is shown in Figure 11.



Figure 11. Image processing methodology

From this image, the centerline is extracted and smoothed via a Gaussian fit. The Gaussian smoothing provides two outputs. The maximum is assumed to be the $\langle c \rangle = 0.5$ location. Using this characteristic height, the area of the turbulent flame is approximated

as a cone which allows for the determination of the turbulent flame speed. Note: the use of a Gaussian fit facilitates the determination of the turbulent flame speed throughout the progress variable field.

The current approach ignores spatial variation of where this $\langle c \rangle = 0.5$ contour may be located across the entire flame, i.e., the flame may not be nominally conical as is assumed in the current approach. To address this limitation, the algorithm was expanded to extract the spatial contour of the progress variable field. This is a valuable addition because the "true" area can be extracted from flame images which gives a better approximation of the actual value of the turbulent flame speed. Of note, however, is that the qualitative trends are not altered; thus, to facilitate comparison across the data collected (previous and newly acquired), the original algorithm that used conical approximation is used in all the data presented here.

2.3 Flame Properties

In the development of models for S_T , it is important that key flame properties corresponding to the laminar condition are measured to facilitate comparison. These key properties are equilibrium quantities, transport properties, laminar quantities and stretched flame quantities. The property and corresponding calculation using the simulation tool in CHEMKIN is described here.

The equilibrium property of primary interest is the adiabatic flame temperature. This value defines the maximum achievable temperature during a combustion process and is calculated using the EQUILIBRIUM module. The adiabatic flame temperature is also useful for determining the ideal density ratio by assuming the perfect gas law and normalizing the flame temperature by the preheat temperature. While the density ratio is understood to have a limited effect on flames at high $u'_{rms}/S_{L,0}$ [75], it is still a potential correlating parameter and is captured for this reason.

The transport properties of interest are the mass diffusivity, kinematic viscosity, and thermal diffusivity. The ratios of these properties provide us with the Lewis, Prandtl and Schmidt numbers all of which provide us information about how a fluid will behave in various conditions. The Lewis number is of greatest interest because of its influence on stretched flame properties.

The primary laminar flame quantities of interest are the laminar flame speed and the thermal flame thickness. To obtain these quantities, the PREMIX simulation is run for each condition and the laminar flame speed is a direct output. Determination of the flame thickness is defined in Equation 17:

$$\delta_F = \frac{(T_b - T_u)}{\left(\frac{dT}{dx}\right)_{max}} \tag{17}$$

where T_b is the burnt flame temperature extracted as the last temperature measurement at the end of the computation domain.

The last set of properties that are calculated are those related to the stretch sensitivity of these mixtures. The calculation of these parameters was detailed in Section 1.2.3. However, a few key parameters of interest but is reiterated here in greater detail. To execute this simulation twin, premixed flames are initialized at a starting exit velocity which is then increased to increase the stretch rate. As the stretch continues to increase, the

simulation approaches extinction where a two-point arc length continuation method is used to follow the branch before terminating when the solution becomes unstable. From this simulation, $S_{L,max}$ which is the maximum stretched laminar flame speed, at the corresponding strain rate the flame thickness is determined using Equation 17 and is referred to as $\delta_{F|S_{L,max}}$. The ratio of these two parameters is defined in Equation 18 below and is used as the characteristic leading point time scale.

$$\tau_{S_{L,max}} = \frac{\delta_{F|S_{L,max}}}{S_{L,max}} \tag{18}$$

Regarding the mechanisms used for the aforementioned calculations, fuel blends containing CH₄ used the GRI 3.0 Mechanism [76], while H₂/CO mixtures used the Davis mechanism [77]. Each mechanism is optimized for a limited range of conditions. GRI 3.0, for instance, uses laminar flame speed targets for CH₄ at pressures up to 20 atm, and preheat temperatures up to 400 K [76]. Many of the conditions for which data have been captured are outside of this range. Additionally, the Davis mechanism was optimized for H₂/CO mixtures, making it unusable to predict kinetics parameters of pure CH₄ fuel blends, and for a limited range of preheat temperatures. The variation of the ability of the mechanisms to predict different fuels and limited range introduce potential uncertainties in the estimation of $S_{L,0}$.

2.4 Uncertainty Analysis

Uncertainty analysis is a necessary aspect of examining experimental data and is used to estimate the possible errors that are associated with a measurement. Uncertainty can typically be broken down into accuracy, which is related to systematic/instrumentation uncertainty, and precision, which accounts for random uncertainty. The outcome of this approach is a range around the measured value within which the true value is assumed to lie.

This range can be influenced by using statistical approaches and quantification of the confidence interval. Confidence intervals are used in statistical analysis to quantify the uncertainty in a sample population to some percentage of confidence assuming the data is normally distributed. Mathematically, they are defined as shown below:

$$\bar{x} = \mu \pm z \left(\frac{s_x}{\sqrt{N}}\right) \tag{19}$$

where \bar{x} is the sample mean, μ is the true mean, z is the coefficient associated with the desired level of confidence, s_x is the sample standard deviation, and N the number of observations/samples.

2.4.1 Systematic Uncertainty (Accuracy)

To determine the uncertainty in the measurement of the turbulent flame speed due to instrumentation uncertainty related to reactant mass flow rate and flame surface area the major inputs in the determination of $S_{T,GC}$. Equation 20 is used to determine the uncertainty related to these two quantities. The sensors utilized for measuring the air flow rate are specified in

Table 1, while those employed for determining the fuel flow rates are listed in

Table 2. The associated fractional uncertainties are included as well.

$$\sigma_{S_{T,GC}} = \sqrt{\sigma_{\dot{m}_R}^2 + \sigma_{A_{}}^2} \tag{20}$$

 Table 1. Fractional systematic uncertainties for sensors involved in air flow rate metering.

Quantity Measured	Transducer	Fractional Uncertainty (%)
Volume Flow Rate	Rosemount 8800-D	0.1
Static Pressure	Omega PX409	0.08
Temperature	Omega K-type Thermocouple	0.75

Table 2. Fractional systematic uncertainties for sensors involved in fuel flow rate metering.

Quantity Measured	Transducer	Fractional Uncertainty (%)
Static Pressure	Omega PX409	0.08
Temperature	Omega K-type Thermocouple	0.75

To determine the accuracy of the reactant flow rate, the sequential perturbation

method is used to combine the uncertainties associated with each sensor. This calculation

is shown for the air mass flow rate and fuel mass flow rate in Table 3 and

Table 4, respectively. The uncertainty estimation in the air mass flow rate is determined by the volumetric flow rate of air which is measured in standard liters per minute; thus, to correct for the density, the pressure and temperature sensors uncertainties are included. The uncertainty estimation shown in

Table 4 includes a discharge coefficient which as described in Section 2.1 is determined

using a Ritter-type drum meter. This coefficient is important as it provides the "real" mass

flow rate through the orifice as opposed to that determined from idealized calculations.

Quantity Measured	Transducer	Δσ (%)	$(\Delta\sigma)^2(\%)$
Volume Flow Rate	Rosemount 8800-D	0.10	0.000100
Static Pressure	Omega PX409	0.08	0.000064
Temperature	Omega K-type Thermocouple	0.75	0.005625
		Overall Uncertainty	0.760855

Table 3. Systematic uncertainty in air mass flow rate metering.

Table 4. Systematic uncertainty in fuel mass flow rate metering.

Quantity Measured	Transducer	Δσ (%)	$(\Delta\sigma)^2(\%)$
Static Pressure	Omega PX409	0.08	0.000064
Temperature	Omega K-type Thermocouple	0.75	0.005625
Discharge Coefficient	Ritter-type Drum Meter	0.50	0.000025
		Overall Uncertainty	0.904931

Estimation of the system uncertainty in the flame area calculation varies case-tocase and can be influenced by humidity and the camera used, making the process completed thus far particularly challenging and potentially unreliable. While not done here, the proper approach of assessing this uncertainty would involve repeating the same experimental condition several times (≥ 2 times) and using statistical analysis to determine the precision uncertainty. By taking this view, the overall system uncertainty is 1.18%.

2.4.2 Random Uncertainty (Precision)

This section examines the random uncertainty, or precision, in the measurement of the turbulent flame speed, as well as a few other derived parameters which will be discussed thereafter. To facilitate analysis of the random uncertainty in the turbulent flame speed, first we simplify Equation 21 to the following:

$$S_{T,GC} = \frac{U_0 r}{\sqrt{r^2 + h_{}^2}}$$
(21)

Here, the primary inputs are the inlet velocity, U_0 , burner radius, r, and flame height, $h_{<c>}$. Because the geometry is fixed, the sources of random uncertainty are in the measurement of inlet velocity and flame height. The inlet velocity random uncertainty is a result of the random uncertainty in volumetric flow rate, pressure, and preheat temperature uncertainties involved in the quantification of the inlet velocity. Determination of the inlet velocity uncertainty is done by examining the measurement thereof during each run and identifying how much it deviates from the value used to process data. For example, data captured at 30 m/s typically – over the course of data collection – range from 29 m/s to 31 m/s. This deviation of ± 1 m/s during data capture was consistent across the datasets, assuming a 95% confidence interval, corresponds to a fractional percentage of approximately $\pm 1.7\%$ for that dataset.

Estimation of the uncertainty in the flame area calculation is primarily based on the image resolutions (1024 x 1024) and the image processing described in Section 2.2. Because a Gaussian fit is used to identify the height over 500 images, the key input into the flame area calculation, a direct output of this fit is the uncertainty in the flame position which is in the range of 0.5 - 1% assuming a 95% confidence interval.

Quantity Measured	Uncertainty Range	Δσ (%)	(Δ σ) ² (%)
Inlet Velocity	±1.7 %	1.7	0.0289
Flame Height	0.5-1%	0.75	0.0056
		Overall Uncertainty	0.0185

Table 5. Uncertainty in $S_{T,GC}$ measurement.

Combining this with the systematic uncertainty from the previous section the leads to an general overall uncertainty of approximately 2.15% in the determination of $S_{T,GC}$.

Another parameter for which random uncertainty is important to consider is that of the root-mean-square turbulent velocity, u'_{rms} . The determination of this value was done at a variety of inlet velocities and blockage ratios after which a linear fit was used to create an empirical model fit. The models for the 12- and 20-mm burners yielded R² values of 0.88 and 0.94, respectively [49, 74]. The R^2 value is given by the following equation:

$$R^2 = 1 - \frac{SS_{residuals}}{SS_{total}}$$
(22)

where $SS_{residuals}$ is the residual sum of squares, and SS_{total} is the total sum of squares. An alternative means of understanding of these two terms are the unexplained variation and the total variation, respectively. This means that the R^2 is a measure of the estimate of explained variance. Thus, assuming unexplained variance can be used to estimate the uncertainty by assuming (1- R^2) is the degree of unexplained variance in u'_{rms} . This yields an approximate uncertainty of 12% and 6% in the 12- and 20-mm burners.

Throughout this work, data will also be plotted against other parameters such as hydrogen content, pressure, preheat temperature, etc. Each of these parameters also have their own uncertainties. For example, data reported to be captured at 300 K may have been captured at 302 K or 299 K and the actual condition for which data are captured can be found in Appendix A. Discrepancies of this manner are more specifically tied to error, i.e., how different the desired condition is from the actual condition. To address this specific concern, data collection did not take place outside of 2% of the desired original condition. Furthermore, these actual conditions are used in the modelling of the kinetics parameters used which as discussed in the prior section are sensitive to the chemical parameter. While not discussed here, the complete estimation of the propagation of said uncertainty is an important consideration.

CHAPTER 3. DISCUSSION OF TURBULENT FLAME SPEED DATA

This section provides an overview of the comprehensive turbulent flame speed database compiled at Georgia Tech. It encompasses data captured for complex syngas fuels as well as hydrogen-doped methane flames. The section begins with a review of the entire database, highlighting the scope and range of the collected data. It also includes a review of previous results and findings related to the database. Following the overall review, subsequent sections delve into specific aspects of the analysis. Section 3.2 focuses on investigating the thermodynamic effects on turbulent flame speed. This involves examining the influence of various thermodynamic parameters on the combustion process and how they affect the turbulent flame speed. In Section 3.3, the analysis shifts to exploring the fuel effects on turbulent flame speed.

3.1 Database Overview

Overall, this database contains approximately 850 measurements divided across three different fuel blends: H₂/CO, H₂/CO/CH₄/N₂ and H₂/CH₄ fuels each corresponding to Datasets 1, 2 and 3, respectively. The specific conditions explored can be found in Appendix A. Note: Datasets 1 and 3 also contain measurement of mixtures containing only CH₄ as fuel. The database has been captured over a large span of time with the author processing and analyzing the data in Dataset 2 [78], and completing the measurement and analysis of the data in Dataset 3.

Parameter	Dataset 1: H ₂ /CO	Dataset 2: H ₂ /CO/CH ₄ /N ₂	Dataset 3: H ₂ /CH ₄
Pressure (atm)	1 - 20	1 - 20	1 – 16
Preheat Temperature (K)	300	350 - 500	300 - 450
Equivalence Ratio	0.4 - 0.9	0.34 - 0.85	0.6 – 0.9
Hydrogen Fraction (%vol.)	0, 30 – 90	27 – 84	0-50
Inlet Velocity (m/s)	4 – 50	40 - 50	30
Turbulence Intensity (m/s)	0.67 – 14.5	4.4 – 10.3	3.4 - 5.6
Burner Diameter (mm)	12, 20	12	12

Table 6. Parameter Space of Database Conditions

The various datasets span different regimes of premixed turbulent combustion which can be seen in the Borghi-Peters diagram below.



Figure 12. Borghi-Peters Diagram of Turbulent Flame Speed Measurements on the 12 mm Burner.

Most of the data is in the thin reaction zone regime while other points are in the distributed reaction zone. This is significant as these regimes are known to be controlled

with differing physical mechanisms as it pertains to turbulence-chemistry interaction as discussed in Section 1.2.1.



Figure 13. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ for H₂/CO mixtures at a pressure of 1 atm, preheat temperature of 300 K and inlet velocity 30 m/s with equivalence ratio varying as needed with hydrogen content to maintain a constant $S_{L,\theta}$ of 34 cm/s. The fuel compositions of H₂/CO fuel blends are represented as follows 30% H₂ (\blacktriangle), 50% H₂ (\bigtriangledown), 70% H₂(\triangleleft), and 90% H₂ (\triangleright).

The results of the H₂/CO data (Dataset 1) were previously reported in the literature with more detail being available in Refs. [23, 58, 74]; however, key takeaways from that work are as follows. First, it was demonstrated that under a fixed $S_{L,0}$ of 34 cm/s, there are demonstrable sensitivities to hydrogen content, and pressure. At a fixed pressure and inlet velocity and $u'_{rms}/S_{L,0} = 9.5$, a 90/10 H₂/CO flame has $S_{T,GC}/S_{L,0}$ values 1.2 times greater than that of a 30/70 H₂/CO flame as shown in Figure 13.

This demonstrates a significant hydrogen content sensitivity in these fuel blends Alternatively, Figure 14 shows at a fixed hydrogen content, inlet velocity and $u'_{rms}/S_{L,0} =$ 17.2, a 70/30 H₂/CO flame at 10 atm has an $S_{T,GC}/S_{L,0}$ values 2.2 times greater than its 1 atm counterpart.



Figure 14. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ for H₂/CO mixtures at a pressure of 1 atm, preheat temperature of 300 K and inlet velocity 30 m/s with equivalence ratio varying as needed with pressure to maintain a constant $S_{L,\theta}$ of 34 cm/s.

These results suggest significant sensitivities to fuel content and pressure that are important to be considered in modelling. Attempts to capture these sensitivities were applied by normalization by $S_{L,max}$ as shown in Figure 15 below.



Figure 15. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ for H₂/CO mixtures with pressures from 1 to 10 atm, preheat temperature of 300 K and inlet velocity 30 m/s with equivalence ratio varying as needed with pressure to maintain a constant $S_{L,\theta}$ of 34 cm/s. The fuel compositions of H₂/CO fuel blends are represented as follows 30% H₂ (\blacktriangle), 50% H₂ (\blacktriangledown), 70% H₂(\blacktriangleleft), and 90% H₂ (\triangleright).

A key takeaway from this normalization approach is the noticeable collapse of data at each pressure; however, the pressure effect persists. For instance, the average $S_{T,GC}/S_{L,max}$ value at a $u'_{rms}/S_{L,max} = 3$ is 1.7 times great at 5 atm than at 1 atm. To address the limitation of this normalization approach, Venkateswaran *et al.* analyzed this data by hypothesizing a second nondimensional parameter along with this approach could be used to capture the effect of pressure.

The second nondimensional parameter is defined as the ratio of the leading point time scale defined in Equation 18 to a relevant time scale ratio and is hereafter referred to as $Ka_{max,flow}$, where the "flow" refers to the flow time scale, e.g., Taylor time scale.



Figure 16. Relationship of $S_{T,GC}/S_{L,max}$ and $Ka_{max,bulk}$ at a fixed $u'_{rms}/S_{L,max}$ of 3.5 where the bulk refers to the bulk time scale, $\tau_{bulk} = D/U_0$. The fuel compositions of H₂/CO fuel blends are represented as follows 30% H₂ (\blacktriangle), 50% H₂ (\triangledown), 70% H₂(\blacktriangleleft), and 90% H₂ (\triangleright).

In Figure 16, the data is conditioned at a nominal $u'_{rms}/S_{L,max}$ of 3.5 and the data plotted against the time scale ratio based on the bulk flow time scale calculated as $\tau_{bulk} = D/U_0$. The time scale analysis revealed a consistent sensitivity of the data as a function of pressure even across datasets from other authors [58]. However, a key limitation was the current analysis depended on a pressure sensitivity only; meaning any other parameters that scaled monotonically with pressure could replace the time scale. The data captured in Datasets 2 and 3 are used to validate this modelling approach.

 $H_2/CO/CH_4/N_2$ fuels comprise the second dataset in this database and are fuel blends that have been seen in industrial applications. The analysis of this data provides an opportunity for comparison with the results from the H_2/CO data as it is captured at preheat temperatures up to 500 K, pressures up to 20 atm, and inlet velocities up to 50 m/s. The final fuel examined in the database is composed of H_2/CH_4 fuel blends which are aimed at modelling the effect of H_2 -addition to natural gas. The data here are captured at a fixed inlet velocity of 30 m/s but involve a systematic exploration of preheat temperature and pressure effects going up to 450 K and 16 atm, respectively. Note there are nine unique fuel types some of which have the same amount of hydrogen limiting the use of a single, universal legend for which all data can be referenced. Therefore, legends are integrated into each caption for clarity as needed.

3.2 Thermodynamic Effects

3.2.1 Dataset 2 ($H_2/CO/CH_4/N_2$): Pressure effects at constant H_2 Content

To examine the pressure effects, the following figures show each fuel at a nominally fixed equivalence ratio across the pressure range for which data were captured. Data captured at a different equivalence ratio or preheat temperature are excluded to focus on the role of pressure for each fuel. The preheat temperature and equivalence ratios between each fuel, however, is allowed to vary. For example, the nominal equivalence ratio for the 27% H₂ fuel is 0.5, while it 0.67 for the 56.9% H₂ fuel blend. The data in the following figures show an increase in $S_{T,GC}$ with increasing turbulence which aligns with results discussed in Section 1.3.1.



Figure 17. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ for an H₂/CO/CH₄ mixture containing 27% H₂ at 1, 5 and 10 atm.



Figure 18. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ for an H₂/CO/CH₄ mixture containing 40% H₂ from 5, 10, and 15 atm.



Figure 19. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ for an H₂/CO/CH₄ mixture containing 56.9% H₂ from 5, 10 and 20 atm.



Figure 20. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ for an H₂/CO/CH₄ mixture containing 83.5% H₂ from 5, 10 and 20 atm.
In each of the figures above, there is a pronounced sensitivity of $S_{T,GC}/S_{L,0}$ to pressure. For example, for a 40% H₂ flame (Figure 18) at a fixed $u'_{rms}/S_{L,0}$ of 60, increasing pressure from 5 to 10 atm leads to a 1.3 factor increase in $S_{T,GC}/S_{L,0}$. Overall, the data is captured across a large range of pressures often times leading to difficulties in comparisons at fixed $u'_{rms}/S_{L,0}$ (e.g., Figure 19 and Figure 20). This could potentially be associated with a decrease in $S_{L,0}$ with pressure, but also an increase in $S_{T,GC}$ as well which is shown in Figure 21.



Figure 21. $S_{T,GC}$ as a function of pressure for H₂/CO/CH₄/N₂ fuel blends containing 27% H₂ (\bigtriangledown), 40% H₂ (\blacksquare), 57% H₂ (\blacklozenge) and 84% H₂ (\bigstar)

The observed positive correlation with pressure indicates that both values contribute to the net increase in $S_{T,GC}/S_{L,0}$. This is significant as it provides further clarity to why the values are increasing. However, an analysis of the pressure sensitivity of $S_{T,GC}$ across the data presented suggest an average pressure sensitivity of $p^{0.24}$. Given a rough scaling of $S_{L,0}$ is

 $p^{0.5}$, the net sensitivity of $S_{T,GC}/S_{L,0}$ to pressure is $p^{0.75}$. Note: the scaling of $S_{L,0}$ may not be applicable to all mixtures, but is used here as a means of demonstrating the combined pressure sensitivity.

Of particular interest amongst this data is the presence of large $u'_{rms}/S_{L,0}$ values in Figure 20. Said data is associated with data captured at or near the lower flammability limit of the fuel at high pressure and a fixed preheat temperature of 403 K. However, due to the presence of turbulence, it has been reported that this allows the flame to pilot itself thereby allowing the flame to sustain itself without completely extinguishing.

3.2.2 Dataset 3 (H₂/CH₄): Thermodynamic Effects

In this section, the impact of pressure, and preheat temperature on H_2/CH_4 fuel blends are discussed. Both pressure and preheat temperature are unique in that they influence both chemical and fluid mechanics parameters, and an understanding of the way these parameters interact with each other will provide a basis for building a physical model that captures these effects.



Figure 22. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ on a 12 mm diameter burner for H₂/CH₄ fuel blends of 0% H₂ (\bullet), 25% H₂ (\blacksquare), and 50% H₂ (\bigtriangledown).

Figure 22 demonstrates a strong effect of pressure at a fixed $u'_{rms}/S_{L,0}$. For example at a $u'_{rms}/S_{L,0}$ of 15, doubling pressure from 1 to 2 atm increases $S_{T,GC}/S_{L,0}$ by a factor of 2.74, and at a $u'_{rms}/S_{L,0}$ of 20, $S_{T,GC}/S_{L,0}$ increases by a factor of 2.1 when pressure increases from 2 to 4 atm. This increase is due to a simultaneous increase in $S_{T,GC}$ and decrease in $S_{L,0}$. This result is in line with observations from Section 3.2.1.

Figure 23 shows measurements of $S_{T,GC}$ across the entire H₂/CH₄ dataset as a function of preheat temperature. This plot illustrates the nontrivial effect of preheat temperature on $S_{T,GC}$ across all pressures, equivalence ratios, and hydrogen content, where an increase of preheat temperature from 300 to 450 K leads to an average increase of a factor of 2.2. There is no other data in the literature currently that demonstrates the effect of preheat temperature on $S_{T,GC}$ and its potential effects.



Figure 23. $S_{T,GC}$ as a function of T_u on a 12 mm diameter burner for H₂/CH₄ fuel blends of 0% H₂ (•), 25% H₂ (\blacksquare), and 50% H₂ (\blacktriangledown).

To drill down into the specific influences of preheat temperature, Figure 24 shows $S_{T,GC}$ and $S_{T,GC}/S_{L,0}$ as a function of preheat temperature when only the preheat temperature is being changed (i.e., constant equivalence ratio, pressure, and inlet velocity.). First, we note that S_T increases with preheat temperature and scales as $T_u^{1.24}$ at a fixed u'_{rms} while $S_{T,GC}/S_{L,0}$ decreases with preheat temperature as $T_u^{-0.97}$ under the same conditions. This can be attributed to the strong temperature dependence of $S_{L,0}$ relative to $S_{T,GC}$. Said outcome is corroborated by Lin *et al.* where there was a negative temperature dependence for hydrogen-rich fuels [61].



Figure 24. $S_{T,GC}$ (left) and $S_{T,GC}/S_{L,\theta}$ (right)as a function of T_u for the 12 mm diameter burner at 4 atm, equivalence ratio of 0.9, and an inlet velocity of 30 m/s.

Figure 25 shows $S_{T,GC}$ as a function of turbulence parameters both normalized by $S_{L,0}$ and not normalized.



Figure 25. $S_{T,GC}$ as a function of u'_{rms} (left) and $S_{T,GC}/S_{L,\theta}$ as a function of $u'_{rms}/S_{L,\theta}$ (right) for the 12 mm diameter burner at 4 atm, equivalence ratio of 0.9, and inlet velocity of 30 m/s on Dataset 3 for three temperatures: 300 K (blue), 400 K (orange) and 450 K (red).

Similar results can be observed here where for a given u'_{rms} , $S_{T,GC}$ increases by a factor of 1.27 when the preheat temperature is increased from 300 K to 400 K, and

increased by another 1.16 times when preheating is increased from 400 K to 450 K. This leads to an overall increase by a factor of 1.47 for a given, u'_{rms} when T_u is increased by a factor of 1.5. Additionally, when examining $S_{T,GC}/S_{L,0}$ as a function of $u'_{rms}/S_{L,0}$, it is interesting to note that the highest values of both these parameters are associated with the lowest preheat temperatures.

Additionally, at a $u'_{rms}/S_{L,0}$ of 13, a 50 K increase in T_u corresponds to a 5% decrease in $S_{T,GC}/S_{L,0}$. The decrease is potentially a result of the decreasing Reynolds number with increasing preheat temperature. As the Reynolds number decreases, the smaller scales of turbulence are more easily dissipated due to viscosity. This limits the ability for these eddies to wrinkle the flame and generate flame surface area to increase the turbulent flame speed. At the same time, the increase in preheat temperature does increase the reaction rates in the flame. These competing effects can explain the small decrease of only 5% in $S_{T,GC}/S_{L,0}$. These results suggest that the preheat temperature sensitivity demonstrates a nontrivial effect on $S_{T,GC}$ which can manifest themselves through multiple mechanisms that are not present for laminar flame speed scalings. More preheat temperature data should be considered in development of models to better understand the turbulent flame speed.

3.2.3 Review of Thermodynamic Effects

The effect of pressure at fixed u'_{rms} , $u'_{rms}/S_{L,0}$, and $u'_{rms}/S_{L,max}$ all demonstrate a positive correlation with $S_{T,GC}$ and the corresponding normalization. There are various mechanisms by which this can occur. Increasing pressure increases the turbulent Reynolds number and decreases the laminar flame thickness. A larger Reynolds number means there is more energy in small scale turbulence, while a thinner flame allows smaller scale

turbulence to interact with the flame. That combination can facilitate an increase in the flame area leading to a greater turbulent consumption speed. There are also hypotheses that the Darrius-Landau instability is enhanced at higher pressures due to alterations of the characteristic cusping wavelength even at high $u'_{rms}/S_{L,0}$ [35, 62]. The preheat temperature effect demonstrated similar effects on $S_{T,GC}$ again increasing at fixed u'_{rms} ; however, when normalized by either $S_{L,0}$ and $S_{L,max}$, there was a decrease in the corresponding normalized $S_{T,GC}$. The difference in these outcomes is driven by the sensitivity of the laminar flame speeds to the pressure and preheat temperature; however, it may also be associated with the opposing effects of pressure and preheat temperature have on the Reynolds number by either increasing or decreasing it, respectively. Additionally, pressure does not affect the density ratio – a key parameter in the strength of the Darrius-Landau instability – while preheat temperature is inversely correlated with it.

3.3 Fuel Effects

3.3.1 Dataset 2 ($H_2/CO/CH_4/N_2$): Hydrogen content effects at constant pressure

Figure 26 shows plots of $S_T/S_{L,0}$ as a function of $u'_{rms}/S_{L,0}$ for the 4 fuel blends. The loglog plot is provided to show the large range of the parameter space investigated in this dataset. Across fuel blends and pressures there is a monotonic increase in $S_{T,GC}$ with u'_{rms} .



Figure 26. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ on a 12 mm diameter burner on a log-scale for H₂/CO/CH₄/N₂ fuel blends containing 27% H₂ ($\mathbf{\nabla}$), 40% H₂ ($\mathbf{\Box}$), 57% H₂ ($\mathbf{\diamond}$) and 84% H₂ ($\mathbf{\star}$).

Figure 27 shows a plot of $S_{T,GC}/S_{L,0}$ as a function of $u'_{rms}/S_{L,0}$ for all fuels at two pressures to demonstrate the effect of changing fuel composition at different pressures. Across all pressures, the data show the 84% H₂ fuel blend and has the greatest value of $S_{T,GC}/S_{L,0}$.



Figure 27: $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,\theta}$ at various conditions on a 12 mm diameter burner at 5 (left) and 10 atm (right) for H₂/CO/CH₄/N₂ fuel blends containing 27% H₂ ($\mathbf{\nabla}$), 40% H₂ ($\mathbf{\Box}$), 57% H₂ ($\mathbf{\diamond}$) and 84% H₂ ($\mathbf{\star}$).

However, the $S_{T,GC}/S_{L,0}$ values are no longer monotonically ordered by H₂ content, i.e., there is no clear correlation between H₂ content (or, alternatively, the calculated value of $S_{L,max}$) and $S_{T,GC}$. This is contrary to prior work done where $S_{T,GC}$ increases with H₂ content for multi-component fuel blends [4, 30]. A potential confounding factor is the changing equivalence ratio between fuel compositions, which influence both $S_{T,GC}$ and $S_{L,0}$. For example, an increase in equivalence ratio and hydrogen content increases both flame speeds, all other things held constant; therefore, depending on the relative change in either hydrogen content or equivalence ratio $S_{T,GC}/S_{L,0}$ could decrease. Furthermore, the additional fuel components introduce more complexity in interpreting this previously unobserved result.

3.3.2 Dataset 3(H₂/CH₄): Fuel Effects

This section describes the effect of hydrogen addition to natural gas fuel blends across a variety of conditions as described in Table 6. Figure 28 plots S_T as a function of u'_{rms} normalized by $S_{L,0}$, and $S_{L,max}$ on the 12 mm burner for these mixtures.



Figure 28. S_T as a function of u'_{rms} normalized by $S_{L,\theta}$ on a 12 mm diameter burner for H₂/CH₄ fuel blends of 0% H₂ (\bullet), 25% H₂ (\blacksquare), and 50% H₂ (\blacktriangledown).

In the $S_{L,0}$ normalized data, one observes what appears to be a collapse of the data at each pressure. This is contrary to previous results where this normalization exhibits a significant scatter [27]. However, when one examines just 1 atm data as in Figure 29, $S_{L,0}$ appears to be a suitable normalizing parameter for these fuel types. Further examination of this observation of this analysis will be provided in the next chapter.



Figure 29. S_T as a function of u'_{rms} normalized by $S_{L,\theta}$ on a 12 mm diameter burner for H₂/CH₄ fuel blends of 0% H₂ (•), 25% H₂ (**I**), and 50% H₂ (**V**).

Of particular interest is the limited change in $S_{T,GC}$ with increasing hydrogen content. Figure 30 shows the $S_{T,GC}$ increasing by only 20% (on average) when increasing H₂ from 0 to 50% at a fixed u'_{rms} . Said result is consistent with work done by Fairweather *et al.* that showed a small increase in S_T measurements in the spherical bomb configuration [47].



Figure 30. S_T as a function of hydrogen content for H₂/CH₄ fuel blends of 0% H₂ (•), 25% H₂ (\blacksquare), and 50% H₂ (\blacktriangledown).

Additionally in laminar flame speed modelling done to examine the effects of hydrogen addition on natural gas and pure CH₄, Petersen *et al.* noted that increasing H₂ content from 0 to 50% only doubled $S_{L,0}$, and beyond this value $S_{L,0}$ dramatically increases [79]. This suggests that more dramatic changes in $S_{T,GC}$ may occur at H₂ contents greater than 50%.

3.3.3 Review of Fuel Effects

Hydrogen content plays a significant role in changing $S_{T,GC}$ particularly in multicomponent fuel blends. In two-component fuel blends, at both a fixed equivalence ratio and under constant $S_{L,0}$, $S_{T,GC}$ increases with increasing H₂ content (i.e., Datasets 1 and 3). However, when the fuel blend contained three or more components, as in Dataset 2, there was a non-monotonicity in the H₂ content effect. Despite the lack of monotonicity, the highest H₂ had the largest $S_{T,GC}$ across each pressure. Additionally, while normalization by $S_{L,0}$ appears to capture hydrogen effects for H₂/CH₄ flames that normalization proved to have limited ability to properly correlate data in Datasets 1 and 2.

3.4 Final Remarks

This section examined the thermodynamic and fuel sensitivities of $S_{T,GC}$ across a wide variety of conditions and fuel classes. By expanding the pressure and preheat temperature data, this work has improved the understanding of the turbulent flame speed sensitivities to both parameters. Most noteworthy, is the reinforcement of the observations related to pressure effects and the novel data showing the impact of preheat temperature over a large range of temperatures for many fuels. Additionally, this work has introduced more fuel classes to existing database: H₂/CO/CH₄/N₂ and H₂/CH₄. The former fuel class is representative of real fuel blends seen in industrial applications and provides a basis for examining if the modelling approaches used are effective in real life applications. The latter fuel class, H₂/CH₄, has been studied in prior work, but not at the high pressure and preheat temperatures discussed in this work. Overall, this has allowed us to achieve the first two objectives of this thesis; namely, to be expand the Georgia Tech turbulent flame speed database, and to explore the sensitivities the turbulent flame speed has to a variety of parameters. The next chapter addresses the final objective one of this work which is examine alternative modelling approaches to better understand the complex interplay of fluid mechanic, fuel, and thermodynamic effects on the turbulent global consumption speed.

CHAPTER 4. SCALING ANALYSIS OF TURBULENT FLAME SPEED DATA

Thus far, we have identified trends of parameters that influence the turbulent flame speed for a variety of mixture types across a plethora of operating conditions. Furthermore, past work identified a combined scaling of $\frac{S_{T,GC}}{S_{L,max}} = f\left(\frac{u'}{S_{L,max}}, \frac{\tau_{S_{L,max}}}{\tau_{flow}}\right)$ is a sufficient to capture pressure and fuel effects [23]. However, this approach is limited in its ability to generalize beyond these specific effects, i.e., any parameter that scales monotonically with pressure could replace the time scale ratio. This chapter explores the robustness of various scaling approaches to the new data that has been measured.

Section 4.1 focuses on the application of just the normalization by $S_{L,max}$ and its efficacy across each of the datasets. The sections that follow all focus on two parameter correlation. The approach in each of these sections is to identify a second parameter that exhibits the same relationship when changed by pressure and preheat temperature independently. Correlating parameters that meet these criteria are then explored further. Section 4.2 explores the Karlovitz number as the second correlating parameter, Section 4.3, the Reynolds number, and Section 4.4 explores the acceleration ratio. Lastly, Section 4.5 summarizes the takeaways from the analysis approach.

4.1 $S_{L,max}$ correlation

The correlation of $S_{T,GC}$ with $S_{L,max}$ assumes that the relationship in the data is of the form shown in the Equation 23 below:

$$\frac{S_{T,GC}}{S_{L,max}} = f\left(\frac{u'}{S_{L,max}}\right)$$
(23)

This basis for this approach is described in Section 1.2.3 with the primary ability of this normalization being its ability to account for the mixture's stretch sensitivity. The impact of this approach is shown in Figure 31 below for the entire Georgia Tech Database.



Figure 31. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ at various conditions on a 12 mm diameter burner.

An immediate observation is the smaller range of both the x- and y-axes which span within a single order of magnitude whereas data that was normalized by $S_{L,0}$ spanned two orders of magnitude for H₂/CO/CH₄/N₂ fuels (Dataset 2) alone. The impact of this normalization on Dataset 1 is shown in Figure 32 below.



Figure 32. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ on a 12 mm burner diameter for Dataset 1 where 30% H₂ (\blacktriangle), 50% H₂ (\triangledown), 70% H₂(\blacktriangleleft), and 90% H₂ (\triangleright).

The main observation is the ability for the normalization to capture fuel effects at a fixed pressure. Figure 33 and Figure 34 show the impact of this normalization on Datasets 2 and 3, respectively. A primary difference between Dataset 1 and Datasets 2 and 3 is that the data on the 12 mm burner (discussed here) was captured at a nominally constant $S_{L,0}$ of 34 cm/s. In Dataset 2 and Dataset 3, some of the data is captured at the same $S_{L,0}$ value; however, generally the flame speed is allowed to freely vary with the operating condition.



Figure 33: $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ at various conditions on a 12 mm diameter burner for Dataset 2 with 27% H₂ ($\mathbf{\nabla}$), 40% H₂ ($\mathbf{\Box}$), 57% H₂ ($\mathbf{\diamond}$) and 84% H₂ ($\mathbf{\star}$).



Figure 34. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ at various conditions on a 12 mm diameter burner for Dataset 3 with 0% H₂ (\bullet), 25% H₂ (\blacksquare), and 50% H₂ (∇).

In Dataset 2, this normalization was insufficient to capture fuel effects which may be attributed to the wider range of preheat temperature and pressures explored in the data. On the other hand, this normalization approach shows some promise in Dataset 3 as shown in Figure 35.



Figure 35. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ at various conditions on a 12 mm diameter burner for Dataset 3 with 0% H₂ (•), 25% H₂ (**I**), and 50% H₂ (**V**) at a pressure of 1 atm, U₀ = 30 m/s, and $\phi = 0.9$.

Here, we note the collapse of the hydrogen containing H₂/CH₄ fuels while the 0% fuel does

not collapse. This is observed at higher pressures as well as shown in Figure 36 below.



Figure 36. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ at various conditions on a 12 mm diameter burner for Dataset 3 with 0% H₂ (•), 25% H₂ (\blacksquare), and 50% H₂ (\blacktriangledown) at 8 atm and 30 m/s.

The limited collapse of 0% H_2 was observed in prior work [58]. A possible explanation for this outcome may be related to the Lewis number of CH₄ mixtures being near unity at the equivalence ratios studies (ϕ =0.9) in this and the prior work referenced. Thus, despite being a negative Markstein length fuel, the enhancement of the flame speed is not as pronounced as fuels containing more H_2 that have a lower Lewis number and are thereby more thermodiffusively unstable. To explore the impact of constant $S_{L,0}$ data between datasets, we compare Dataset 1 and 2 under the normalization by $S_{L,max}$ in Figure 37 which examines a subset of the data conditioned on pressure, laminar flame speed and inlet velocity.



Figure 37. $S_{T,GC}$ as a function of u'_{rms} normalized by $S_{L,max}$ at a pressure of 5 atm, inlet velocity of 50 m/s, and nominal laminar flame speed of 34 cm/s between Datasets 1 and 2 where 30% H₂ (\blacktriangle), 50% H₂ (\triangledown), 56.9% H₂ (\diamondsuit), 70% H₂(\blacktriangleleft), and 90% H₂ (\triangleright)

Between the two datasets, there is a distinct lack of collapse of the data, which suggests that the difference in preheat temperature which is nominally 120 K plays a role in limiting the ability of $S_{L,max}$ normalization to fully capture preheat temperature effects. This observation suggests that normalization by only $S_{L,max}$ is unable to capture both

pressure and preheat temperature effects motivating the need for a second parameter. With this in mind, we next explore incorporation of time scale effects.

4.2 *S_{L,max}* and Time Scale Ratio correlation

This correlation approach assumes that the data has the relationship shown in Equation 24.

$$\frac{S_{T,GC}}{S_{L,max}} = f\left(\frac{u'}{S_{L,max}}, Ka_{max,flow}\right)$$
(24)

This Karlovitz number assumes the data can be represented by a ratio of the leading points time scale and some flow time scale as shown in Equation 25.

$$Ka_{max,flow} = \frac{\tau_{S_{L,max}}}{\tau_{flow}}$$
(25)

Here $\tau_{S_{L,max}}$ is the time scale associated with the critically stretched flame and defined by Equation 26,

$$\tau_{S_{L,max}} = \frac{\delta_{F|S_{L,max}}}{S_{L,max}} \tag{26}$$

where $\delta_{F|S_{L,max}}$ is the thermal flame thickness at $S_{L,max}$ determined as shown in Equation 17. In Equation 25, τ_{flow} is a chosen flow time scale, e.g., the Taylor time scale. In the plots presented, the time scale used will be $\tau_{turb} = \ell_0/u'_{rms}$; however, alternative time scales are presented in Appendix B.

The current Karlovitz number definition in this work uses the thermal flame thickness. As much of the data discussed is in the thin reaction zone, eddies can significantly alter the preheating process leading to so-called flame thickening and potentially making the thermal thickness a poor length scale choice. Still an important consideration is the turbulence that will be interacting with the highly strained flame front. At these critically stretched points, the flame thickness is much thinner. For instance, a 90/10 H₂/CO at 1 atm, 300 K and an equivalence ratio of 0.48, the maximum stretched flame thickness is 6% of the unstretched value. Similarly, methane at similar thermodynamic conditions but an equivalence ratio of 0.9, has a value 72% of its unstretched value, suggesting there is an influence of fuel composition. To visualize this, the Borghi-Peters diagram is replotted using $S_{L,max}$ and $\delta_{F|S_{L,max}}$ shown in Figure 38.



Figure 38. Borghi-Peters diagram using velocity and length scales associated with max stretched values.

One immediate observation is the changes in regime locations as compared to that shown in Figure 12. Most notable is the H₂/CO/CH₄/N₂ (Dataset 2) data, where much of the data was in the broken reaction zone, now being mostly in the corrugated flamelets regime. Secondly, most of the data are now in the corrugated flame regime suggesting that physically the turbulent eddies no longer directly influence impact the internal flame structure as the flame is too thin relative to the eddy. Thus, the thermal flame thickness is sufficient as an appropriate flame length scale. With this major point discussed, data is examined as a function of $Ka_{max,turb}$ at a fixed $u'_{rms}/S_{L,max}$. An example of this is shown in Figure 39.



Figure 39. $S_{T,GC}/S_{L,max}$ as a function of $Ka_{max,turb}$ for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ values of 3.5 (•) and 6.5 (•) for Dataset 1 where τ_{flow} is $\tau_{turb} = l_0/u'_{rms}$.

The data plotted is for Dataset 1 for two different values of $u'_{rms}/S_{L,max}$. While there is some scatter in the data, there is a consistent correlation of $S_{T,GC}/S_{L,max}$ and the Karlovitz number across pressure and fuel compositions in this dataset with relatively slower chemistry being associated with lower normalized turbulent flame speed values.

As stated in the prior section, the goal of this analysis approach is to identify if the inclusion of this second parameter sufficiently captures both pressure and preheat temperature effects. This analysis is shown in the following figures where $S_{T,GC}/S_{L,max}$ is shown as a function of $Ka_{max,turb}$ as a function of only pressure (Figure 40) or preheat temperature (Figure 41) at a fixed $u'_{rms}/S_{L,max}$.



Figure 40. $S_{T,GC}/S_{L,max}$ as a function of $Ka_{max,turb}$ when changed only with pressure for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 6 at a preheat temperature of 300 K where τ_{flow} is $\tau_{turb} = l_0/u'_{rms}$.



Figure 41. $S_{T,GC}/S_{L,max}$ as a function of $Ka_{max,turb}$ when changed only with preheat temperature for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 6.5 at a pressure of 5 atm where τ_{flow} is $\tau_{turb} = l_0/u'_{rms}$.

In both figures, the negative correlation of $S_{T,GC}/S_{L,max}$ and time scale ratio is consistent suggesting that this choice of parameters is sufficient to capture both thermodynamics and fuel effects. Given that the chosen flow time scale used here is invariant to thermodynamic changes, the chemical time scale must control this relationship. Given this outcome, this approach is expanded across all datasets where pressure and preheat temperature are allowed to freely vary in Figure 42.



Figure 42. $S_{T,GC}/S_{L,max}$ as a function of $Ka_{max,turb}$ for a 12 mm burner diameter for all data at a fixed $u'_{rms}/S_{L,max}$ of 6.25 for Dataset 1 (•), Dataset 2 (\blacksquare), and Dataset 3 (\blacklozenge) where τ_{flow} is $\tau_{turb} = l_0/u'_{rms}$.

This data shows a consistent trend when each of the datasets are shown; however, there is still significant scatter suggesting that a third parameter may be needed to correlate the scatter in the data. In Section 4.1, it was noted that each of these datasets were taken with different conditions in mind with the varying $S_{L,0}$ being identified as a parameter that was allowed to vary freely. Figure 43 shows the same data as Figure 42; however, the groupings are shown based on $S_{L,0}$.



Figure 43. $S_{T,GC}/S_{L,max}$ as a function of $Ka_{max,turb}$ for a 12 mm burner diameter for all data at a fixed $u'_{rms}/S_{L,max}$ of 6.25 for Dataset 1 (•), Dataset 2 (\blacksquare), and Dataset 3 (\blacklozenge) where τ_{flow} is $\tau_{\text{turb}} = I_0/u'_{rms}$.

Given the promise this modelling approach shows, we next assume a simple power law relationship between the model parameters and $S_{T,GC}/S_{L,max}$ and examine its efficacy at explaining the relationship in the data. This power law relationship takes on the form shown in Equation 27:

$$\frac{S_{T,GC}}{S_{L,max}} = C \left(\frac{u'}{S_{L,max}}\right)^a \left(Ka_{max,turb}\right)^b \tag{27}$$

where C, a and b are constants determined using regression modelling. For this model C = 0.15, a = 1.58, and b = -0.16.



Figure 44. Actual $S_{T,GC}/S_{L,max}$ values compared to the predicted values using power law relationship described in Equation 27.

This modelling approach leads to a R^2 value of 0.67 suggesting that $u'_{rms}/S_{L,max}$ and $Ka_{max,turb}$ when used in this form can capture about 67% of the variance in $S_{T,GC}/S_{L,max}$. While not poor, this R^2 value could likely be improved with more data, a more robust modelling approach (e.g., response surface modelling), and or the inclusion of another parameter. An important note here (as discussed in Sections 2.3 and 2.4) is the values used to develop this empirical model involved a parameter, $S_{L,max}$, that is modelled using a chemical mechanism. Thus, the model is directly impacted by the propagation of said error through this regression approach.

4.3 S_{L,max} and Reynolds number correlation

This correlation approach assumes that the data has the relationship shown in Equation 28.

$$\frac{S_T}{S_{L,max}} = f\left(\frac{u'}{S_{L,max}}, Re_t\right)$$
(28)



Figure 45. $S_{T,GC}/S_{L,max}$ as a function of Re_t for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ values of 3.5 (•) and 6.5 (•) for Dataset 1.

In Figure 45, the relationship of $S_{T,GC}/S_{L,max}$ as a function of Re_t is shown to be positively correlated which aligns with results presented in the literature. This initial look at the data suggests that this could be another potential correlating parameter. To validate said hypothesis, we take the same approach as the prior section to determine if the Reynolds number scaling is robust to both pressure and preheat temperature sensitivities. Figure 46 and Figure 47 show the same conditions as in Figure 37 and Figure 39 except as a function of Reynolds number.



Figure 46. $S_{T,GC}/S_{L,max}$ as a function of Re_t when changed only with pressure for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ of 6 and preheat temperature of 300 K.



Figure 47. $S_{T,GC}/S_{L,max}$ as a function of Re_t when changed only with preheat temperature for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 6.5 at a pressure of 5 atm.

Of note is the inverse relationship between the pressure and preheat temperature variations this is likely driven by the Reynolds number sensitivity where it scales as p^{1} or $T_{u}^{-3/2}$. Because these dependencies change between the two sensitivities, this indicates that the Reynolds number is not a suitable parameter of choice for capturing both fuel and thermodynamic effects again motivating a third parameter. Lastly, we examine the acceleration ratio as a potential correlating parameter.

4.4 *S_{L,max}* and Acceleration ratio correlation

This correlation approach assumes that the data has the relationship shown in Equation 29.

$$\frac{S_{T,GC}}{S_{L,max}} = f\left(\frac{u'}{S_{L,max}}, \frac{a_{flame}}{a_{flow}}\right)$$
(29)

The question of the impact of turbulence on how flames accelerate has been investigated primarily through phenomenological arguments [80]. This section attempts to quantify the ability of a flame to accelerate based on its unstretched value, $S_{L,0}$, and its maximum stretched value, $S_{L,max}$. The motivation behind this approach can be observed when comparing the two fuels with the same $S_{L,0}$ but appreciably different $S_{L,max}$ values. For example, a 30/70 H₂/CO mixture and a 25/75 H₂/CH₄ mixture with an $S_{L,0}$ of 34 cm/s have $S_{L,max}$ values of 94 cm/s and 74 cm/s, respectively. This implies the H₂/CO mixture will ultimately propagate 1.3 times faster, but also will likely do it faster based on it having a smaller chemical time scale. To conceptualize flame acceleration, we begin with a model problem of a flat laminar flame propagating into a spatially varying velocity with zero mean velocity and allow it to propagate. According to the work completed by Shin [81] the flame will, after an initial transient, reach a steady state shape as shown in Figure 48 with similar outcomes being described in Ref [21] for an alternative model problem.



Figure 48. Figure depicting the initial and final flame shapes of model problem in Ref [81].

In both model problems, the laminar flame speed is assumed to be constant; however, in negative Markstein length fuels the positively curved points will continue to propagate to some steady state value which can be shown to be $S_{L,max}$. To expand this argument flame acceleration, we employ a kinematic argument as shown in Equation 30:

$$a_{flame} = \frac{\Delta V_{flame}}{\Delta t} = \frac{S_{L,max} - S_{L,0}}{t_{SS} - 0} \rightarrow \frac{\Delta S_L}{t_{SS}}$$
(30)

where t_{ss} is the "time" to a steady state flame. This value is expected to scale with a chemical time scale, which here will be considered the critical stretch strain rate. Flow acceleration is derived by dimensional considerations as shown in Equation 30.

$$a_{flow} \sim \frac{L}{t^2} \sim \frac{{u'}^2}{\ell_0} \tag{31}$$

Thus, an approximate definition of the acceleration ratio is given by Equation 32.

$$\frac{a_{flame}}{a_{flow}} = \frac{(\Delta S_L)\ell_0}{\tau_{chem} \, u'^2} = \left(\frac{\ell_0}{\tau_{chem} \, u'}\right) \left(\frac{\Delta S_L}{u'}\right) = Ka \left(\frac{S_{L,max}}{S_{L,0}} - 1\right) \left(\frac{u'}{S_{L,0}}\right)^{-1} \tag{32}$$

Each of the terms in this equation are significant. First, the Karlovitz number, Ka, appears suggesting that this time scale ratio is important in controlling the degree of relative acceleration. Furthermore, because the Karlovitz number is based on a general chemical time scale, different time scales (e.g., extinction strain rate, leading point time scale, etc.) could be substituted into this equation. For the purposes of this analysis, we use the leading points time scale making the Karlovitz number equivalent to that explored in Section 4.2. The second term, $\frac{S_{L,max}}{S_{L,0}} - 1$, shows the importance of the relative values of the stretched and unstretched flame speeds. Large values of this term indicate a wide range over which the flame can be stretched and are likely to be found in more stretch sensitive mixtures. For negative Markstein length fuels, this value is always greater than one. The final term is the inverse of $\frac{u'}{S_{I,0}}$ which can be thought of a measure of relative wrinkling intensity. Furthermore, as was discussed in Section Error! Reference source not found., the flame a t maximum stretch can be in a different regime on the Borghi-Peters diagram than the unstretched flame suggesting that the way the flow field interact with the flame may change as it accelerates.

With a general overview of this new parameter presented, Figure 49 and Figure 50 shows the data at a fixed $u'/S_{L,max}$ across the entire database.



Figure 49. $S_T/S_{L,max}$ as a function of a_{flame}/a_{turb} for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 3 where $a_{turb} = u'_{rms}^2/l_0$.



Figure 50. $S_T/S_{L,max}$ as a function of a_{flame}/a_{turb} for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 6.25 where $a_{turb} = u'_{rms}^2/l_0$.

Consistent in both figures is the positive correlation of $S_T/S_{L,max}$ and a_{flame}/a_{flow} suggesting that when the flame can accelerate more than the flow, you can expect higher turbulent flame speeds. While this result is promising, it does not necessarily guarantee that this modelling approach is sufficient to capture thermodynamic effects. Like previous sections, we identify if this metric can capture pressure (Figure 51) and preheat temperature effects (Figure 52).



Figure 51. $S_{T,GC}/S_{L,max}$ as a function of a_{flame}/a_{turb} when changed only with pressure for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ of 6.25 and preheat temperature of 300 K where $a_{turb} = u'_{rms}^2/l_0$.


Figure 52. $S_{T,GC}/S_{L,max}$ as a function of a_{flame}/a_{turb} when changed only with pressure for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ of 6.25 and preheat temperature of 300 K.

Like the Reynolds number and Karlovitz number scalings, there is an increase in $S_{T,GC}/S_{L,max}$ with a_{flame}/a_{turb} when it is increased with just pressure. However, when preheat temperature is considered there is no discernible relationship between the two variables. While this does mean this combination of correlating parameters is insufficient, a trend or relationship may become clear with more data or with the inclusion of a third parameter.

4.5 Remarks

This chapter examined four normalization schemes for $S_{T,GC}$ across a wide range of fuel, fluid mechanic and thermodynamic parameters. Of the four, only the correlation that uses both $u'_{rms}/S_{L,max}$ and $Ka_{max,turb}$ showed promise for correlating data across fuel and thermodynamic effects.

This modelling approach was originally developed to incorporate non-quasi steady effects as a means of measuring how well a flames internal chemistry can track with the time varying stretch rate at the leading point. Prior to this work, incorporation of a time scale ratio was identified to sufficiently capture fuel and pressure effects; however, there was not enough data to identify if it generalized to preheat temperature effects which is sensible as increasing pressure and preheat temperature both lead to faster chemical time scales. Nevertheless, there was not a complete collapse of the data which was attributed to the laminar unstretched flame speed which will require further investigation.

Incorporation of the Reynolds number as the second parameter in the modelling equation was unsuccessful. On average, there was an increase in $S_{T,GC}/S_{L,max}$ with turbulent Reynolds number. Because a larger range of scales are present, there are more ways for different length scales to interact with the flame which can lead to greater surface area and thereby an increase in $S_{T,GC}/S_{L,max}$. However, when the preheat temperature is used to change the turbulent Reynolds number, there is an inversion of this relationship. A potential explanation of this is simply because $S_{L,max}$ is more sensitive to preheat temperature than $S_{T,GC}$ which follows conclusions from Chapter 3 related to $S_{T,GC}/S_{L,0}$.

Lastly, the concept of the acceleration ratio was introduced as the second modelling parameter and it was shown that $S_T/S_{L,max}$ appears to have a positive correlation with the acceleration ratio. While this trend was consistent on average, when examined in the framework defined to identify if a modelling approach was sufficient, the approach is unsuccessful. Specifically, the pressure showed a positive correlation, and the preheat temperature data showed no discernible correlation. Overall, this chapter has identified a modelling approach that shows significant promise in capturing the effect of flow, fuel and thermodynamic effects on the turbulent flame speed thereby allowing us to address the final objective of this thesis.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This chapter reviews the major findings of this work and identifies potential avenues for future work.

5.1 Major Findings and Contributions

Throughout this work, the importance of measuring, interpreting, and modelling $S_{T,GC}$ was emphasized and served as the central theme of this thesis. In Chapter 2, the experimental methodology used to expand the existing database of turbulent flame speed measurements was discussed along with the expected uncertainty in not only the turbulent flame speed, but also other parameters that would be used to analyze it. Chapter 3 presented an overview of the H₂/CO data that was initially captured to use a launching point for analysis of the H₂/CO/CH₄/N₂ data and presentation and investigation of novel H₂/CH₄ measurements. Chapter 4 leveraged all this data to assess four different modelling approaches with the hope of identifying a physics-based model that could capture the sensitivity of the turbulent flame speed to fuel, flow and thermodynamic effects.

Through this process, the Georgia Tech database has now been expanded beyond just H_2/CO fuel blends, and now includes measurements and analysis of $H_2/CO/CH_4/N_2$ and H_2/CH_4 satisfying the first objective of this thesis. The addition of these measurement measurements facilitated a deeper understanding of the sensitivities of $S_{T,GC}$ to fuel, fluid mechanic and thermodynamic effects. The data presented not only further reinforced prior results demonstrating that increasing pressure leads to an increase in the turbulent flame

speed, but also showed the impact of preheat temperature. Most notably, a 150 K increase in preheat temperature leads to 1.5 factor increase in $S_{T,GC}$ across all u'_{rms} when all other parameters are held constant. Identification of this sensitivity is important and adds to the limited literature that directly explores preheat temperature effects. Furthermore, data collected includes high pressure, and preheat temperature measurement of H₂/CH₄ fuel blends which are not currently present in the literature. The outcomes allowed us to satisfy the second objective of this work, i.e., examining the data to understand various sensitivities.

Lastly, using the data captured at these now broader conditions allowed us to test the robustness of four correlating expressions developed to capture the effects. The data detailed in this thesis corroborates prior finding related to large differences in turbulent flame speeds for the same $S_{L,0}$ and u'_{rms} , it also presented novel limitations of existing data scaling techniques. For instance, the inability of $S_{L,max}$ normalization alone to capture fuel effects when the thermodynamic conditions are being varied as they were in Dataset 2. Or, for said normalization to collapse data with 0% H₂ as seen in Dataset 3. Nevertheless, this motivated the exploration of another correlating parameter capable of capturing the variation within the database. Specifically, this led to the identification of a Karlovitz number based on the leading point time scale and various turbulent flow time scales as the optimal second parameter to $u'_{rms}/S_{L,max}$ for modelling the turbulent flame speed's sensitivity in the database. The value in this cannot be understated as this approach able to correlate a wide range of fuel, fluid mechanic, and thermodynamic conditions. There are, however, some limitations that are noted that will require further investigation.

The other two correlations presented were of great value for two major reasons. First, prior work had hypothesized that the Reynolds number scaling along with $u'_{rms}/S_{L,max}$ would potentially have limitations given that it could be replaced with anything that scales pressure. The data presented confirmed that limitation. Finally, the acceleration ratio-based correlation offered a novel way to view/interpret the data using a new parameter. While this correlation did not show much success; it does, however, open the door to exploring a new way to interpret existing measurements.

5.2 **Recommendations of Future Work**

Based on the conclusions obtained in this work future work should focus on the following areas:

- 1. The analysis conducted in this work heavily relies on the leading points concept. However, the current line-of-sight chemiluminescence measurements are insufficient to capture the locations of leading points along the flame from. Therefore, simultaneous OH planar laser induced fluorescence (PLIF) and particle image velocimetry (PIV) data would be useful in extracting strain and curvature statistics at the flame front. These derived measurements can then be compared to existing strain rate measurements and used to evaluate the approach adopted in this work. Furthermore, exploring how thermodynamic effects impact these statistics could enhance the understanding of the underlying physics associated with changes in pressure or preheat temperature.
- 2. The data presented in this thesis for H_2/CH_4 mixtures extends up to 50% with only a small change in turbulent flame speed. To further explore the impact of

hydrogen, extending the hydrogen content to up to 95% may yield interesting results. Additionally, more data that is collected across more preheat temperature and pressures will facilitate an opportunity to further test the robustness of the correlations examined in this work.

3. There is significant scientific and industrial interest in leveraging ammonia as a hydrogen carrier in fuel systems. Ammonia, however, has very different burning characteristics burning at about the same adiabatic flame temperature as natural gas/air mixtures at an equivalence ratio of 1, but with a maximum laminar flame speed of only 7 cm/s compared to natural gas at 40 cm/s. Similar to this work which studied the effects of hydrogen addition, more research is needed to quantify and understand the effects ammonia addition to the combustion process some which has already begun [55, 82].

4. The correlating expression developed in this work showed significant promise to correlate data across a variety of conditions but did still exhibit some scatter which would necessitate a third parameter. Alternatively, there may be another set of parameters entirely that can collapse the data. For instance, in Figure 38 the impact of S_{L,0} on the scatter using the scaling of Equation 24 was identified. This may suggest that there is a proper "reference" laminar flame speed that is optimal across the entire database. Said identification would be of great value to the combustion and allow for potential correlation of data across different groups.

APPENDIX A. EXPERIMENTAL CONDITIONS

This appendix details the test conditions discussed in this thesis. While only the fuel content, pressure, preheat temperature and inlet velocity are noted, the data does contain sweeps of turbulence at up to five conditions which will be noted in the table description. Table 7 denotes the conditions tested for Dataset 1 which contains H_2 /CO fuels which have five turbulence sweeps.

Hydrogen	Pressure (atm)	Temperature	Equivalence	Inlet Velocity
Content (% vol.)		(K)	Ratio	(m/s)
30	1	300	0.61	30
50	1	300	0.55	30
70	1	300	0.51	30
90	1	300	0.48	30
30	1	300	0.61	30
50	1	300	0.55	30
70	1	300	0.51	30
90	1	300	0.48	30
30	5	300	0.75	30
50	5	300	0.68	30
70	5	300	0.63	30
50	10	300	0.75	30
30	1	300	0.61	20
90	1	300	0.48	20
30	1	300	0.61	50
70	1	300	0.51	50
90	1	300	0.48	50
30	5	300	0.75	50
50	5	300	0.68	50
70	5	300	0.63	50
90	5	300	0.59	50
50	10	300	0.75	50
30	10	350	0.84	50
70	10	300	0.70	50

Table 7. Experimental test conditions of Dataset 1.

Table 8 denotes experimental test conditions of Dataset 2 which contains $H_2/CO/CH_4/N_2$ fuels. The CO/CH₄/N₂ content for these fuels are not included because these blends are proprietary. They do, however, represent practical syngas fuels that come from feedstocks and are being used in industrial applications. Each data point has five turbulence sweeps.

Hydrogen	Pressure (atm)	Temperature	Equivalence	Inlet Velocity
Content (% vol.)		(K)	Ratio	(m/s)
27	5	408	0.51	40
27	10	379	0.5	40
27	15	404	0.49	40
27	20	400	0.61	40
40	5	433	0.69	40
40	10	416	0.59	40
40	20	417	0.55	40
56.9	1	346	0.66	50
56.9	5	418	0.68	50
56.9	10	418	0.66	50
56.9	20	488	0.85	40
83.5	5	420	0.45	50
83.5	10	422	0.41	50
83.5	20	403	0.35	50

 Table 8. Experimental test conditions of Dataset 2.

Table 9 denotes experimental test conditions of Dataset 3 which contains H_2/CH_4 fuels. Each data point contains a turbulence sweep of four points except for those that are denoted with an asterisk. These conditions only contain one data point due to experimental limitations of the system.

Hydrogen	Pressure (atm)	Temperature	Equivalence	Inlet Velocity
Content (% vol.)		(K)	Ratio	(m/s)
0	1	300	0.9	30
0	2	300	0.85	30
0	2	300	0.9	30
0	2	300	1	30
0	4	300	0.75	30
0	4	300	0.8	30
0	4	300	0.9	30
0	4	300	1	30
0	2	350	0.9	30
0	6	350	0.7	30
0	6	350	0.8	30
0	6	350	0.9	30
*0	8	375	0.7	30
*0	8	375	0.8	30
*0	8	375	0.9	30
*0	12	375	0.7	30
*0	12	375	0.8	30
*0	16	425	0.7	30
*0	16	425	0.8	30
0	8	375	0.9	30
0	4	400	0.9	30
0	4	450	0.9	30
0	8	400	0.82	30
0	8	400	0.9	30
25	1	300	0.82	30
25	1	300	0.9	30
25	2	300	0.82	30
25	4	300	0.82	30
25	4	350	0.82	30
25	4	350	0.9	30
25	8	400	0.82	30
25	8	400	0.9	30
50	1	300	0.73	30
50	1	300	0.9	30
50	2	300	0.73	30
50	4	300	0.73	30
50	4	350	0.73	30
50	8	300	0.73	30
50	8	400	0.73	30

Table 9. Experimental test conditions of Dataset 3.

APPENDIX B. ALTERNATIVE FLOW TIME SCALE NORMALIZATIONS

In this appendix, additional plots showing the relationship of $S_T/S_{L,max}$ alternative correlating parameters across different time and acceleration scales.

B.1 Time Scale Ratio Correlations at Other Flow Time Scales



Figure 53. $S_T/S_{L,max}$ as a function of $Ka_{max,turb}$ when changed only with pressure for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 6 at a preheat temperature of 300 K where τ_{flow} is $\tau_{bulk} = D/U_0$.



Figure 54. $S_T/S_{L,max}$ as a function of $Ka_{max,turb}$ when changed only with pressure for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 6 at a preheat temperature of 300 K where τ_{flow} is $\tau_{turb} = l_0/u'_{rms}$.



Figure 55. $S_T/S_{L,max}$ as a function of $Ka_{max,turb}$ when changed only with pressure for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ of 6 at a preheat temperature of 300 K where τ_{flow} is $\tau_{\text{int}} = l_0/U_0$.



Figure 56. $S_T/S_{L,max}$ as a function of $Ka_{max,turb}$ when changed only with preheat temperature for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ values between each condition where τ_{flow} is $\tau_{\text{bulk}} = D/U_{\theta}$.



Figure 57. $S_T/S_{L,max}$ as a function of $Ka_{max,turb}$ when changed only with preheat temperature for a 12 mm burner diameter at a fixed $u'_{rms}/S_{L,max}$ values between each condition where τ_{flow} is $\tau_{\text{int}} = l_0/U_0$.

B.2 Acceleration Ratio Correlations at Other Flow Time Scales



Figure 58. $S_{T,GC}/S_{L,max}$ as a function of a_{flame}/a_{turb} when changed only with pressure for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ of 6 and preheat temperature of 300 K where $a_{bulk} = U_0^2/D$.



Figure 59. $S_{T,GC}/S_{L,max}$ as a function of a_{flame}/a_{turb} when changed only with pressure for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ of 6 and preheat temperature of 300 K where $a_{int} = u'_{rms}/\tau_{int}$.



Figure 60. $S_{T,GC}/S_{L,max}$ as a function of a_{flame}/a_{turb} when changed only with preheat temperature for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ of 6.5 and pressure of 5 atm where $a_{bulk} = U_0^2/D$.



Figure 61. $S_{T,GC}/S_{L,max}$ as a function of a_{flame}/a_{turb} when changed only with preheat temperature for a 12 mm burner diameter at fixed $u'_{rms}/S_{L,max}$ of 6.5 and pressure of 5 atm where $a_{int} = u'_{rms}/\tau_{int}$.

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