Thermal Ignition

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To Leslie, Juliane, Jane, Helmut, Frank, & Trey

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Abstract

Accidental ignition of flammable gases is a critical safety concern in many industrial applications. Particularly in the aviation industry, the main areas of concern on an aircraft are the fuel tank and adjoining regions, where spilled fuel has a high likelihood of creating a flammable mixture. To this end, a fundamental understanding of the ignition phenomenon is necessary in order to develop more accurate test methods and standards as a means of designing safer air vehicles. The focus of this work is thermal ignition, particularly auto-ignition with emphasis on the effect of heating rate, hot surface ignition and flame propagation, and puffing flames.

Combustion of hydrocarbon fuels is traditionally separated into slow reaction, cool flame, and ignition regimes based on pressure and temperature. Standard tests, such as the ASTM E659, are used to determine the lowest temperature required to ignite a specific fuel mixed with air at atmospheric pressure. It is expected that the initial pressure and the rate at which the mixture is heated also influences the limiting temperature and the type of combustion. This study investigates the effect of heating rate, between 4 and 15 K/min, and initial pressure, in the range of 25 to 100 kPa, on ignition of n-hexane air mixtures. Mixtures with equivalence ratio ranging from $\phi = 0.6$ to $\phi = 1.2$ were investigated. The problem is also modeled computationally using an extension of Semenov's classical auto-ignition theory with a detailed chemical mechanism. Experiments and simulations both show that in the same reactor either a slow reaction or an ignition event can take place depending on the heating rate. Analysis of the detailed chemistry demonstrates that a mixture which approaches the ignition region slowly undergoes a significant modification of its composition. This change in composition induces a progressive shift of the explosion limit until the mixture is no longer flammable. A mixture that approaches the ignition region sufficiently rapidly undergoes only a moderate amount of thermal decomposition and explodes quite violently. This behavior can also be captured and analyzed using a one-step reaction model, where the heat release is in competition with the depletion of reactants.

Hot surface ignition is examined using a glow plug or heated nickel element in a series of premixed

n-hexane air mixtures. High-speed schlieren photography, a thermocouple, and a fast response pressure transducer are used to record flame characteristics such as ignition temperature, flame speed, pressure rises, and combustion mode. The ignition event is captured by considering the dominant balance of diffusion and chemical reaction that occurs near a hot surface. Experiments and models show a dependence of ignition temperature on mixture composition, initial pressure, and hot surface size. The mixtures exhibit the known lower flammability limit where the maximum temperature of the hot surface was insufficient at igniting the mixture. Away from the lower flammability limit, the ignition temperature drops to an almost constant value over a wide range of equivalence ratios $(0.7 < \phi < 2.8)$ with large variations as the upper flammability limit is approached. Variations in the initial pressure and equivalence ratio also give rise to different modes of combustion: single flame, re-ignition, and puffing flames. These results are successfully compared to computational results obtained using a flamelet model and a detailed chemical mechanism for n-heptane. These different regimes can be delineated by considering the competition between inertia, i.e., flame propagation, and buoyancy, which can be expressed in the Richardson number.

In experiments of hot surface ignition and subsequent flame propagation a ~ 10 Hz "puffing" flame instability is visible in mixtures that are stagnant and premixed prior to the ignition sequence. By varying the size of the hot surface, power input, and combustion vessel volume, we determined that the instability is a function of the interaction of the flame with the fluid flow induced by the combustion products rather than the initial plume established by the hot surface. The phenomenon is accurately reproduced in numerical simulations and a detailed flow field analysis revealed a competition between the inflow velocity at the base of the flame and the flame propagation speed. The increasing inflow velocity, which exceeds the flame propagation speed, is ultimately responsible for creating a puff. The puff is then accelerated upward, allowing for the creation of the subsequent instabilities. The frequency of the puffing is proportional to the gravitational acceleration and inversely proportional to the flame speed. We propose a relation describing the dependence of the frequency on gravitational acceleration, hot surface diameter, and flame speed. This relation shows good agreement for lean and rich n-hexane-air as well as lean hydrogen-air flames.

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Chapter 1

Introduction

1.1 Motivation

Accidental ignition of flammable gases is a critical safety concern in many industrial applications. Particularly in the aviation industry, the main areas of concern on an aircraft are the fuel tank and adjoining regions, where spilled fuel has a high likelihood of creating a flammable mixture. To this end, a fundamental understanding of the ignition phenomenon is necessary in order to develop more accurate test methods and standards as a means of designing safer air vehicles.

Following the TWA 800 accident on July 17, 1996, the National Transportation Safety Board (NTSB) investigated the fuel tank flammability and fuel tank ignition sources (NTSB, 2000). The results of investigation led the NTSB to recommend that the FAA find a means to eliminate flammable mixtures in the fuel tanks. In 2008, the FAA created a requirement to install an inerting system to eliminate flammability, particularly for heated center fuel tanks by reducing the oxygen content below 12%. As part of the NTSB investigation, several research projects were carried out at the Explosion Dynamics Laboratory at California Institute of Technology including: "Flash Point and Chemical Composition of Aviation Kerosene (Jet A)" (Shepherd et al., 1999), Spark Ignition Energy Measurements in Jet A (Shepherd et al., 1997). While not directly addressed in the final FAA rule-making, the reduction or elimination of possible ignition sources is an essential part of engineering design practices for aircraft and industries with flammability hazards. In this regard, Shepherd et al. (1997) investigated the required ignition energy for Jet A, while Bane et al. (2011) showed that kerosene mixtures have comparable minimum ignition energy to the lean hydrogen mixtures used for certification. The lean hydrogen mixtures were assumed to have lower ignition energies and thus using them as test mixtures would have an inherent safety margin. In light of the findings by Bane et al. (2011) we were motivated to investigate the test standards currently in use for thermal

ignition, i.e., in heated vessel of by hot surfaces. There are of course other potential ignition sources such as open flames, electrical streamer discharges, hot and burning particles, but these were not the focus of this study.

For safety aspects, several different temperatures are important for the characterization of a particular fuel. Colwell and Reza (2005) describe how the temperature required for ignition increases given the situation. For example, the flash point is the temperature above which a pool of liquid fuel has sufficient vapor pressure to be ignited by a pilot flame (ASTM, 2010). The flash point of Jet A lies in the range of 43–66 °C (Colwell and Reza, 2005, CRC, 1983, NFPA 325, 1994). If we were to take the flash point as a general upper bound for any design temperature, we would be unable to boil water for coffee or tea on an aircraft. This, of course, it not the case since no open flame is present near the fuel tank, by design.

For ignition from hot elements, the particular quantity of interest is the temperature that leads to ignition of a flammable atmosphere without a flame present. A measure of this temperature is defined as the auto-ignition temperature. The auto-ignition temperature standard test is to inject a fuel into a heated vessel and determining by visual inspection if ignition has occurred within 10 minutes (ASTM, 2005). For many applications, the auto-ignition temperature determined from this standard test is what is then used to define limiting (highest) temperature of hot surfaces in region where flammable vapor may be present. However, this test has many limitations, which are explored in the following chapters. The flame propagation resulting from an ignition of a premixed fuel-air mixture determines the pressure rise and thus potential structural damage resulting from an accidental ignition, and must also be considered. The ignition process is a complicated interaction of chemical heat release, encompassing the competition between chain branching and terminating reactions, heat transfer into and out of the system, and fluid mechanics. To mitigate the risk of accidental explosions in industrial facilities and on aircraft in the aviation industry, the mechanisms and parameters leading to ignition must be investigated. The ultimate goal is to use our better understanding of the thermal ignition process and auto-ignition tests to further improve the safety of aviation and other industrial systems operating with flammable mixtures.

1.2 Background

Seminal work in the area of ignition by hot surfaces was done by Davy (1817) while investigating explosions in coal mines (Babrauskas, 2003). Davy describes a common way of lighting the mines as:

> "a steel wheel, which, being made to revolve in contact with flint, affords a succession of sparks: but this apparatus always requires a person to work it; and, though much less liable to explode the fire-damp than a common candle, yet it is said to be not entirely free from danger."

In his experiments, Davy was unable to ignite a combustible coal gas (firedamp) mixture with a hot iron rod, unless the iron rod itself is burning. The first explanation of this effect (Babrauskas, 2003) was given by Mallard and Le Chatelier in 1880. They concluded that a sufficiently long time is necessary for the gas to stay in contact with the hot surface in order for the mixture to ignite.

Thornton (1919) was among the first to perform experiments on the current required to ignite various gaseous mixtures by electrical wire, with particular focus on the hazard that arises from broken light bulbs in coal mines. In this work, measurements were performed at elevated pressures using water to compress the gas, and it was concluded that ignition by hot wires is independent of pressure, but changes with wire diameter. These experiments, however, are incomparable to the atmospheric tests since the absorption into the water and water vapor content are not accounted for.

In 1927, Coward and Guest investigated the ignition of natural gas and air mixtures by heated nickel bars of varying size, composition, hot surface material, and flow velocity above the hot surface. The work concluded that the ignition temperature depends on the mixture composition, but an explanation was not provided. Coward and Guest observed that wider heated bars reduce the temperature required for ignition, and that flow over hot surface, created by a fan, could either decrease or increase the ignition temperature depending on the speed.

Scott et al. (1948) used an early version of the auto-ignition test apparatus, which would later become the ASTM E 659 test shown in Figure 1.1. Experimental auto-ignition temperatures are given for a multitude of compounds as part of the experiments at the Bureau of Mines in Pittsburgh, PA.

The Bureau of Mines continued their work, which was published in part in Zabetakis et al. (1954) and Kuchta et al. (1965), performing a wide range of experiments on auto-ignition and hot surfaces using a variety of fuels. In these investigations, experiments were conducted to test the effect

ASTM E 659 – 78 (2005)
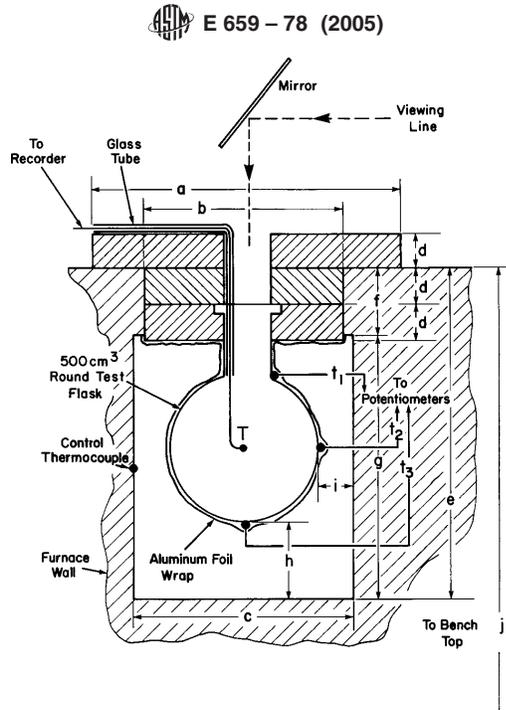
Figure 1.1: ASTM E 659 auto-ignition temperature apparatus (reprinted, with permission, from ASTM (2005), copyright ASTM International)

of surface area and volume on auto-ignition in quiescent mixtures, with the work on hot surfaces performed in a slow flowing reactor. The results of these efforts included a scaling relationship for the ignition temperature as a function of the natural logarithm of the (hot) surface area as shown in Figure 1.2. However, the effects of the surface geometry or orientation are not considered, and consequently the scaling laws extrapolated from theory developed by Semenov (1940) only hold for a limited range of hot surface areas.

The graph reproduced in Figure 1.2 is also found in Babrauskas (2003) without the data points. While the trends developed by Semenov (1940) are supported by this data, the broad application of this work should be taken very cautiously as the control over composition and flow velocity are very limited.

We separate the investigation of thermal ignition into the goal of finding the lowest possible temperature at which a gaseous mixture will ignite, i.e., auto-ignition, and the required temperature for less favorable geometries such as isolated hot surfaces.
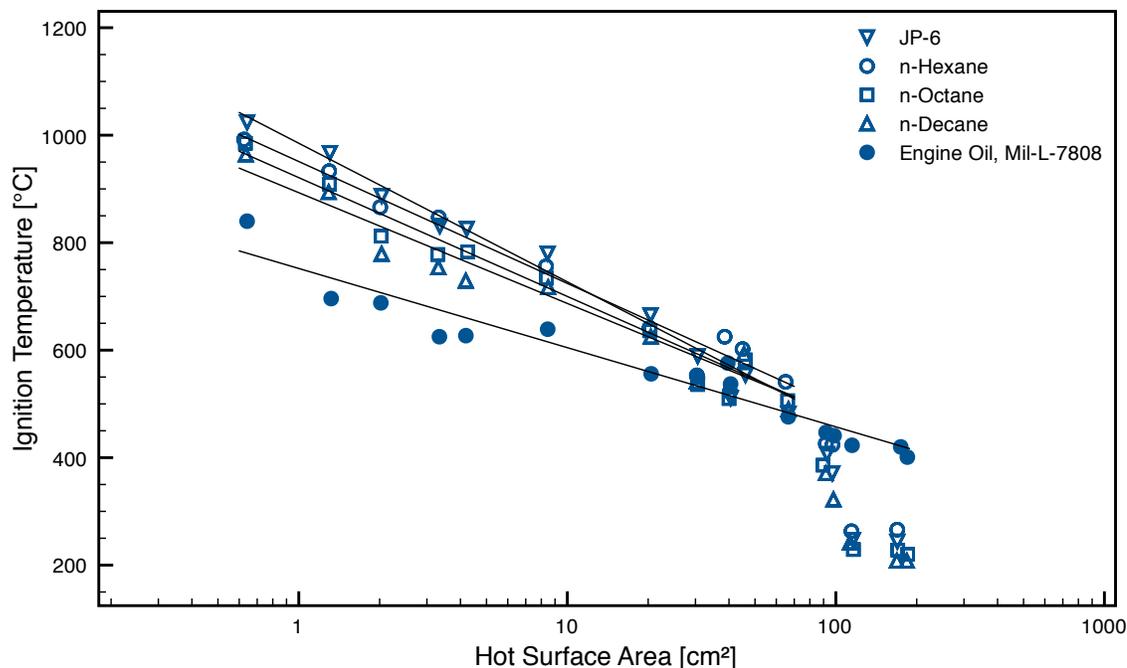
Figure 1.2: Ignition as a function of hot surface size (reproduced from Kuchta et al., 1965)

1.2.1 Thermal Ignition in a Heated Vessel — Auto-Ignition

Ignition is the process of initializing an exothermic chemical reaction that can lead to a propagating flame or detonation. Ignition can occur through the generation of highly reactive species (radicals), whose production rate is in competition with their destruction rate, as well as the competition of chemical heat release and heat loss to walls, which determines the mixture temperature and thus the reaction rates. In general, combustion of hydrocarbon fuels is separated into slow reaction, cool flames, and ignition regimes based on pressure and temperature (Glassman, 2008, Pilling, 1997).

Slow reactions occur when fuel is in contact with an oxidizer at temperatures below the ignition temperature (Babrauskas, 2003). The fuel and oxidizer react, but do so without a rapid increase in pressure, and the heat released by the oxidation is lost to the environment. Since the reaction rate is a strong function of temperature, these reactions will not take place at a temperature far below the ignition temperature (Babrauskas, 2003).

Cool flames occur at temperatures higher than slow reaction and below the ignition temperatures (Babrauskas, 2003). This lower temperature leads the reaction down a different path, creating peroxides as reaction products, which are only partially oxidized and thus release less energy than if the reaction had gone to completion (e.g., CO_2 and H_2O for hydrocarbon oxygen reac-

tions) (Babrauskas, 2003). The resulting flames have a pale blue color, and can exhibit oscillatory behavior (Yang and Gray, 1969). Townend et al. (1934) were the first to map at what temperatures and pressures ignition and cool flames of hexane air mixtures occur.

From a chemical reaction perspective, ignition is characterized by a "rate of chain carrier generation exceeding the chain termination reaction" - or in other words, a runaway reaction (Glassman, 2008). In this case, the reaction releases energy and thus speeds up the reaction rate if that energy cannot be lost to environment at a sufficiently fast rate. The reaction then leads to a pressure and temperature rise until the reactants are consumed.
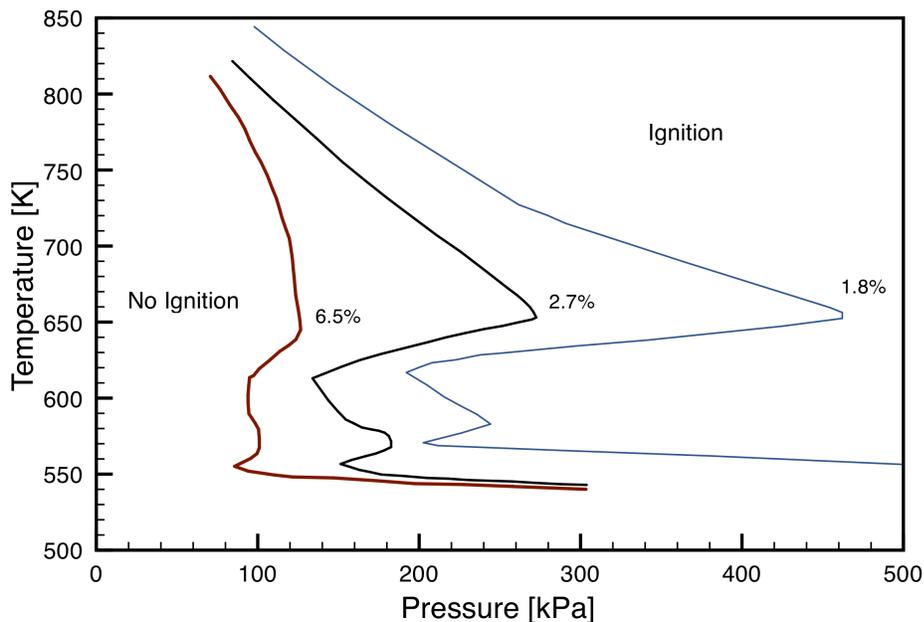
Figure 1.3: Regions of ignition as a function of temperature and pressure for n-hexane for several molar concentrations of n-hexane in air (Townend et al., 1934) (Figure adapted from Babrauskas, 2003)

A classical view of how ignition, nonignition and cool flames are separated as function of temperature and pressure is given for n-hexane as shown in Figure 1.3 (Townend et al., 1934). At low temperature and low pressure some radical species may be formed. Due to the low pressure, the diffusivity is high and they recombine into stable species at wall, which means that testing vessels of different material can have different explosion limits (Warnatz et al., 2006).

The auto-ignition temperature is not a universal quantity and depends on the substance and molecular structure of the fuel as well as the oxidizer and whether or not any diluent are present, e.g., the nitrogen in air. For this investigation, we are interested in fuels like hexane that have comparable auto-ignition temperatures to aviation kerosene (see Table 1.1). The combustion characteristics

and path of pure substances are far more easy to characterize than those of complex hydrocarbon fuels such as Jet A, which consists of many different species of paraffins, iso-paraffins, aromatics, naphthenes, and olefins (Shepherd et al., 1999).

Table 1.1: Selected minimum auto-ignition temperatures (AIT) at one atmosphere from Kuchta (1985) and CRC (1983)

Fuel	AIT [°C]	
	in air	in oxygen
Hydrogen	520	$\sim$400
Methane	630	500
Propane	450	N/A
n-Hexane	225	220
Gasoline (100/130)	440	315
Kerosene	230	215
Turbine Fuel	238	N/A

While the ASTM E659 is a standard test for the auto-ignition temperature, only the minimum temperature for ignition at atmospheric pressure is investigated (ASTM, 2005, Colwell and Reza, 2005, Pilling, 1997). The specific mixture composition is not controlled because liquid test fuel is injected directly into an open heated vessel. The contents are not actively mixed, and it is presumed that "a considerable range of composition exist within pockets of gas in the vessel as evaporation of liquid fuel, or mixing of the injected gaseous fuel, occurs" (Pilling, 1997).

In prior laboratory research, the combustion products have either been condensed and the liquid analyzed later (Bailey and Norrish, 1952), or a gas chromatograph was used to analyze a small sample at a maximum frequency of about 0.1 Hz (Wilk et al., 1986). Additional work was done in rapid compression machines at higher temperatures, 600–800 K (Griffiths et al., 1993), and gas sampling techniques (Ribaucour et al., 1992, Vanhove et al., 2006). While pressure transients are easily captured in these experiments, fast and accurate fuel concentration measurements requiring optical techniques have never previously been applied to the auto-ignition phenomenon.

The present work includes tests conducted using hexane as a surrogate for kerosene, with the experimental setup addressing problem of the control over gas composition, allowing for testing at varying pressures, and precise control over the heating rate, which has been identified as an important factor (Mason and Wheeler, 1922). Additionally, the current study allows for continuous measurements of the fuel concentration.

1.2.2   Thermal Ignition from a Concentrated Hot Surface

Isolated hot surfaces surrounded by a flammable mixture such as a pipe carrying hot gas in a flammable leakage zone in an aircraft or the overheating of a failing device, are potential ignition sources. For design purposes, it is important to understand the dependence of the ignition temperature on hot surface size and geometry since limiting space restrictions may lead to unfeasible design solutions. While, standardized tests exist to evaluate various properties of fuels, including the ASTM E659 (ASTM, 2005) for auto-ignition temperature of fuels, and the ASTM D56 (ASTM, 2010) for flash point, no standard test exists for hot surface ignition (Smyth and Bryner, 1997).

As mentioned before, Coward and Guest (1927) investigated hot surface ignition of natural gas-air mixture by various heated metal surfaces, but the control over the flow velocity at the hot surface and visual observations were limited. Platinum surfaces were found to be catalytic, but the ignition temperatures were higher than those of noncatalytic nickel. Kuchta et al. (1965) extended the work at the Bureau of Mines, varying the size and geometry of the hot surfaces, but with limited control over the composition and flow over the hot surface. The hot surface of interest is heated to a given temperature inside a flow reactor and then a mixture of fuel and air is passed over it at a specified flow rate. However, the exact mixture composition is unknown and the flow velocity at the hot surface can only be roughly estimated based on the overall flow rate and vessel size.

Gray (1970) analytically investigated the effect of surface area to volume ratio. The work follows the work of Kuchta et al. (1965) and White (1967) who concluded from experimental data that increasing the surface area in a fuel tank, e.g., by inserting metal honeycomb, increases the safety. Gray pointed to the negative temperature coefficient behavior of larger hydrocarbon as an alternate source for the behavior.

Ono et al. (1976) studied the ignition of stoichiometric mixtures of methane, propane, ethyl-alcohol, and diethylether in air by a vertical hot plate inside a combustion vessel. Measurements of the flow velocity were performed by particle image velocimetry. The choice of geometry is quite useful in comparisons with simulations and analytical models for flow along a heated vertical plate (Tritton, 1988). The temperature of the hot surface is initially kept at a temperature just below the ignition temperature and then raised to initiate ignition. As mentioned earlier, slow reactions can take place at temperatures just below the ignition temperature and change the composition of the mixture.

Laurendeau (1982) performed a wide literature review of available hot surface ignition data for various hydrocarbon fuels, particularly methane. The data collected was used to derive a simple correlation relating the ignition temperature to various parameters. Also taken into account in

the model is the flow outside the hot surface, such as stagnant, free, and forced convection. The value of this model is to give general trends of the ignition temperature, but does not provide accurate numerical values. Laurendeau points out that detailed information about the experiments and application are necessary to make accurate comparisons, including the surface size, orientation, geometry, mixture composition, and temperature history leading to ignition.

Kumar (1989) focused his experiments on hydrogen-oxygen-diluent mixtures. The combustion of hydrogen differs from that of hydrocarbon fuel. In addition, its high diffusivity will change the hot surface ignition characteristics relative to hydrocarbon fuels, which must be kept in mind when comparing the results of ignition experiments and simulations. It is still very relevant for many applications including loss-of-cooling events in nuclear power plant like Fukushima–Daiichi on March 11, 2011.

Kumar also developed a model of solving the transport and energy conservation equation using an explicit scheme, that requires very small time steps down to 1 ns for accurate solutions. The equations describe the ignition from a hot surface in one dimensional unsteady condition with the gas at temperature below the hot surface temperature and the chemistry uses a reduced mechanism for hydrogen-oxgyen-diluent combustion. In the experiments and simulations, the effects of pressure, mixture concentration, diluent, and initial gas temperature were investigated with relatively good agreement for most parameters.

In an effort to create a standardized test for hot surface ignition, Smyth and Bryner (1997) at the National Institute of Standards and Technology (NIST) performed a large number of experiments testing the temperature required for ignition of a gas mixture flowing over a heated metal foil. In this work, the foil was placed at 45° for a constant residence time of 150 ms, and a wide variety of fuels and hot surface materials were examined. From the results given in their study, the temperature are higher than even those of Kuchta et al. (1965) at comparable surface size, which would indicate that the residence time was too short to activate any low temperature chemistry. Additionally, the geometry chosen for the experiment is very difficult to reproduce computationally (Shepherd, 2012).

Babrauskas (2003) points out that hot surface ignition can be investigated in a similar manner to the auto-ignition tests, where no uniform heating eliminates convection. For hot surfaces, this could be achieved by placing the hot surface at the top of the vessel and thus stably stratifying the mixture, however, no such experiments have been performed.

1.2.3   Hot Surface Ignition of Liquid Fuels

A special type of hot surface ignition is ignition of liquid fuel droplet by hot surfaces. This process is significantly more complex due to the breakup of droplet, evaporation of the fuel and mixing with the air necessary to crate a flammable mixture. However, the connection to the work presented here is clear and thus worth mentioning. In 2005, Colwell and Reza performed a large number of tests using droplets of fuel impinging a hot surface and evaluating the ignition probability as a function of temperature. While the work included a thorough review of thermal ignition testing on available data, an extrapolation of their results to the fundamental physical and chemical processes leading to hot surface ignition is difficult. The complexity of the experiments performed is too great to use analytical models or even perform simulations and a statistical approach is taken to characterize the likelihood of ignition as a function of temperature. A thorough literature review of ignition of liquid droplets was done by Bennett (2001).

In this study, we explore the conditions leading to ignition and compare these to high quality computational results. Our goal is to develop sufficiently realistic and detailed models so that these ignition thresholds and ignition transients can be accurately predicted.

1.2.4   Cyclic Flame Propagation in Premixed Combustion

The process of thermal ignition of a flammable mixture by a hot-surface and the subsequent flame propagation is important to the fundamental understanding of combustion, as well as industrial safety applications. Flame instabilities are of particular interest since they can affect the flame propagation speed and increasing the flame surface area and accelerating the flame speed. This chapter focuses on a global flame instability, i.e., a flickering or puffing flame, rather than small scale instabilities at the flame front.

Flames propagating with a flickering or puffing behavior with frequencies around 10 Hz have been discussed since the First International Symposium on Combustion in September 1928 (Chamberlin and Rose, 1948). Chamberlin and Rose were among the first to make quantitative measurements of the oscillation frequencies observed in Bunsen burners. For a range of gases (e.g., natural gas, hydrogen, carbon monoxide, butane, and ethane), the rate of flame oscillations was observed to be "on the order of 10 per second". The oscillations were quantified by tracking the tip location of the flame. Chamberlin and Rose observed that frequency changed with the size of the injection nozzle, and the origin of the flicker was attributed to an alternating rate of diffusion of oxygen into the flame

The oscillation of non-premixed gaseous flames have since then been investigated experimentally by Kimura (1965), Toong et al. (1965), Durao and Whitelaw (1974), Grant and Jones (1975), Strawa and Cantwell (1989) and Durox et al. (1996).

Kimura (1965) investigated propane jet flames, which exhibited periodic oscillations (10–15 Hz) above a critical injection velocity. Premixing the propane with air suppressed these oscillations. After investigating the temperature and velocity profile, he concludes that the oscillations are caused by the instability of the laminar jet flow.

Toong et al. (1965) observed these instabilities for flames created by burning liquid fuel at the end of a probe in air to simulate droplet combustion. They postulate that "it is quite likely that the onset of the self-sustained flame oscillations is due to the amplification of the Tollmien-Schlichting waves, in the region where the Reynolds Number is greater than the critical value." However, Grant and Jones (1975) argue that based on their experiments and those of Durao and Whitelaw (1974), linear stability theory is insufficient in explaining how the frequency is invariant over a large range of parameters.

The jet injection velocity was substantially reduced in the experiments conducted by Durox et al. (1996). In fact, in their theoretical analysis the injection velocity is assumed to be negligible and the flame instability is attributed to a shear layer created by the buoyancy induced velocity on the flow behind the flame front. In their study, the effect of pressure and gravitational acceleration were tested by performing the experiment on parabolic flights that created microgravity as well as maximum accelerations of 1.8 g.

Buckmaster and Peters (1988) have carried a theoretical analysis of the oscillations associated with a infinite candle. Similar oscillations have also been observed in fires above pools of liquid fuels (Cetegen and Ahmed, 1993) and in room fires (Zukoski, 1986).

These oscillations are not limited to non-premixed flames, but also occur in premixed flames as shown by Durox et al. (1990), Cheng et al. (1999), Shepherd et al. (2005), Guahk et al. (2009), and Tanoue et al. (2010). In these studies, the frequency of the instability is again on the order of 10 Hz. In all of these previous experiments of premixed flames, the gaseous mixture was injected into the burner at a specific injection velocity.

Durox et al. (1990) also performed experiments on parabolic flights of premixed flames to study the effect of varying gravitational acceleration. Additional data is given for the variation of the oscillation frequency as a function of injection velocity (1.45–2.4 m/s), pressure, and equivalence ratio.

Cheng et al. (1999) studied the effects of buoyancy on premixed "V-flames" by considering both gravitation acceleration in the direction of injection and opposed to it. The results were considered as a function of Richardson number, the ratio of inertia to buoyancy force, but "findings point to the need to include both upstream and downstream contributions in theoretical analysis of flame turbulence interactions."

Guahk et al. (2009) investigated the oscillations of conical flames and inverted conical flames. They describe the oscillations as a flame-intrinsic Kelvin-Helmholtz instability.

A combined experimental and numerical approach was taken by Shepherd et al. (2005), who injected a methane-air mixture at 0.73 m/s. The analysis showed that the "flame tip oscillation is caused by a competition between the pressure fields associated with the predominantly radial motion of the burnt gases near the flame front and the rotating vortex motion."

Tanoue et al. (2010) measured the temperature distribution of a premixed methane flame injected at 2 m/s and attribute the instability to a Kelvin-Helmholtz instability.

The experiments and simulations investigated in the present study use a very different configuration than the previous work. Instead of studying jets, a combustible mixture, which is quiescent prior to ignition is examined. The puffing phenomenon occurs in a closed vessel that is filled entirely with a homogeneous combustible mixture and then ignited by a hot surface.

1.3 Thesis Outline

Results from studies on heated vessels subjected to ramp heating are presented in Chapter 2, hot surface ignition in Chapter 3, and premixed puffing flames in Chapter 4. Chapter 2 describes the experimental setup, with additional background for the diagnostic techniques presented in Appendix A and B. Experimental results are presented and discussed here with a complete list of experiments performed given in Appendix I. Additional detail of the theoretical analysis is given in Appendix C and D. Some of the thermodynamic data used in the chemical mechanism was treated for discontinuities as described in Appendix H. Chapter 3 details the dependence of ignition temperature with mixture composition and resulting flame propagation with additional literature and tabular data available in Appendix F. Experimental data and still images are available in Appendix I.2, with color images shown in Appendix L. The puffing phenomenon is described in detail in Chapter 4 with some additional scaling arguments given in Appendix G.