

0.1 Rapid Compression Machine

0.1.1 Experimental Procedure

The studies in this dissertation were conducted using the Rapid Compression Machine (RCM) constructed by Mittal around 2005 and described in the work of Mittal and Sung [1] and Mittal [2]. This RCM has been used to study the autoignition behavior of a number of fuels, including *n*-decane, methylcyclohexane, hydrogen, syngas, dimethyl ether, methanol, toluene, benzene, di-isobutylene, iso-octane, jet fuel, and gasoline [3–18], in addition to the studies presented in this work.

A modern RCM operates by rapidly compressing (hence the name) a test gas mixture to targeted pressure and temperature conditions. The compression is effected by either a single piston or dual, opposed pistons. Upon reaching the targeted state, the piston (or pistons) is stopped and fixed in place so that the reactions proceed in a constant volume reactor. When studying autoignition with an RCM, the primary data are the measured pressure traces during and after the compression stroke. These pressure traces are processed to derive information such as the pressure and temperature at the end of compression (EOC) and the ignition delay. It is also possible to employ laser diagnostics or extract gas samples from the reactor to examine reaction pathways in more detail.

The present RCM is a pneumatically-driven/hydraulically-stopped single-piston arrangement. An image of the RCM without the sampling apparatus described in Sec. 0.2 is shown in Fig. 1 and a schematic with the sampling apparatus is shown in Fig. 2. The RCM consists of four chambers and three pistons that are used to control the machine. The chambers are called the reaction chamber, the hydraulic chamber, the pneumatic chamber, and the driving tank; similarly, the pistons are called the reactor, hydraulic, and pneumatic pistons and each is installed in the chamber of the same name. The rear of the reaction chamber is bolted to the front of the hydraulic chamber; seals in the face of the hydraulic chamber prevent oil from leaking into and contaminating the reaction chamber. The driving tank and the rear of the pneumatic chamber are connected by a union; a seal around the circumference of the pneumatic piston seals gas in the driving tank from the front of the pneumatic

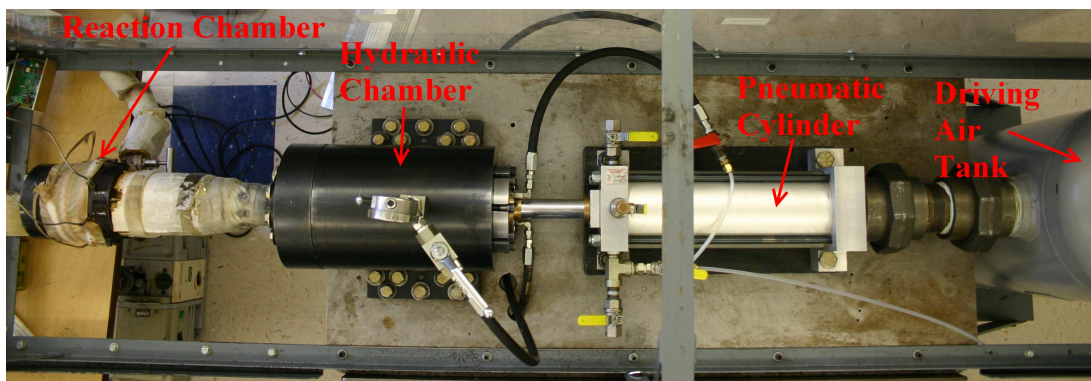


Figure 1: Photograph of the RCM.

chamber. Thus, the pneumatic piston can be driven by pressure from the driving tank on its rear and pressure from the pneumatic chamber on its front. The three pistons are connected by a rod running from the front of the pneumatic piston to the rear of the reactor piston so that they move as one; this will be referred to as the piston assembly.

At the start of an experimental run, with the piston in the EOC position, the reaction chamber is vacuumed to less than 1 torr. Next, the piston assembly is retracted by pressurizing the front face of the piston in the pneumatic chamber. For safety, and to prevent damage to the RCM, the driving tank is filled to limit the acceleration of the piston assembly during the retraction. The pressure on the front of the pneumatic piston pulls the piston assembly rearward and seats the rear of the hydraulic piston onto an O-ring in the rear of the hydraulic chamber. The hydraulic chamber is filled with oil to a pressure of approximately 800 psi, providing a rearward force on the front face of the hydraulic piston. The air pressure is released from the front of the pneumatic chamber and the driving tank is filled to the desired driving pressure. The force on the hydraulic piston opposes the force on the pneumatic piston from the driving tank and the piston assembly remains at rest. The reaction chamber is filled with the required initial pressure of test gas mixture from the mixing tank. Finally, compression is triggered by releasing the hydraulic pressure through an electrically-operated solenoid valve. The piston assembly is driven forward by the unbalanced force from the pressure in the driving tank on the pneumatic piston. The gases in the reaction chamber are brought to the compressed pressure (P_c) and compressed temperature (T_c) conditions

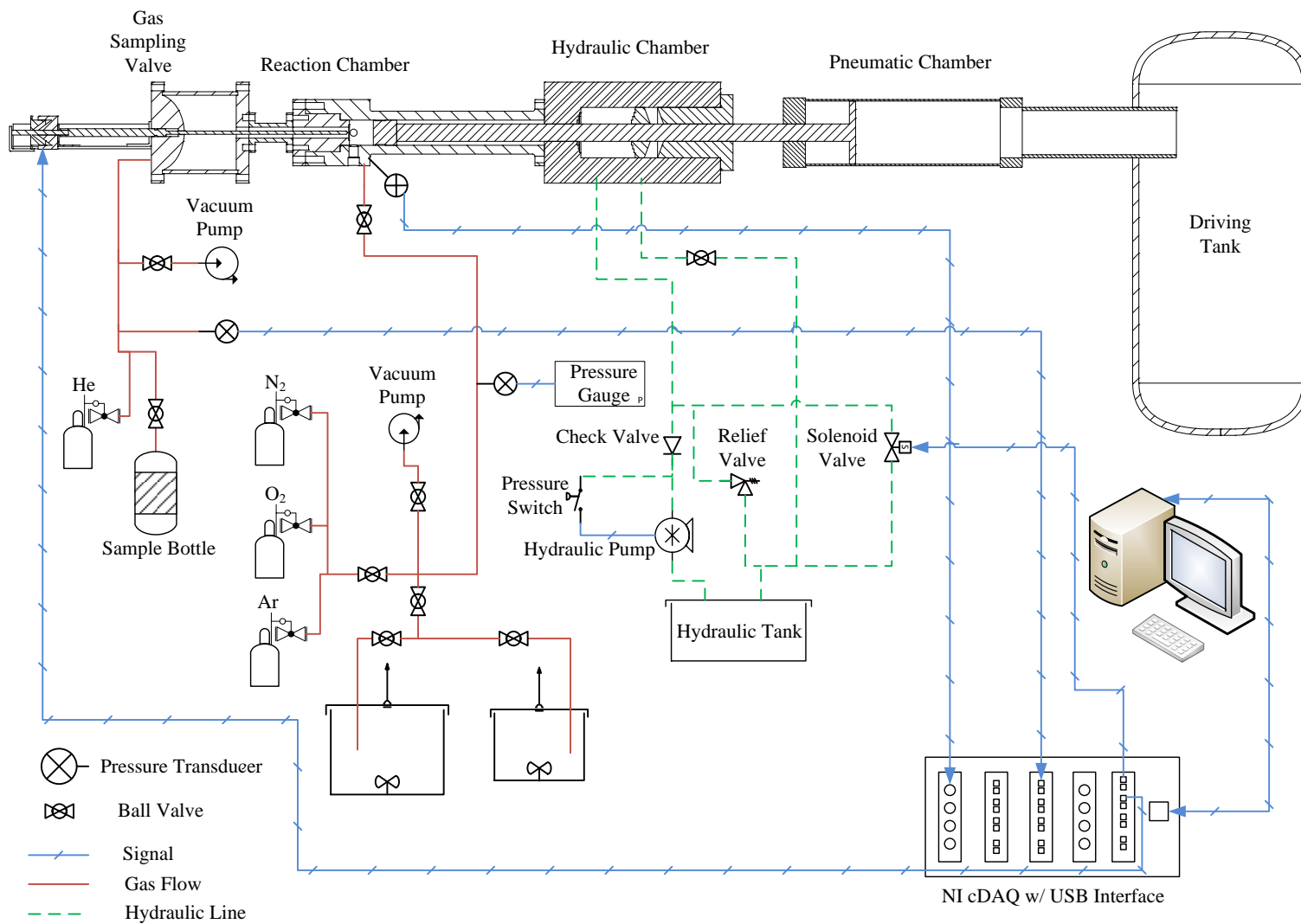


Figure 2: Schematic of the RCM. Not to scale

in approximately 30 ms to 50 ms.

The required driving pressure for a given EOC pressure can be estimated from a force balance between the force on the pneumatic piston from the driving tank and the force on the reactor piston from the test gases, as shown in Eq. (1c).

$$P_{d,\min} \cdot A_p = P_{r,\text{EOC}} \cdot A_r \quad (1a)$$

$$P_{d,\min} \cdot \frac{\pi d_p^2}{4} = P_{r,\text{EOC}} \cdot \frac{\pi d_r^2}{4} \quad (1b)$$

$$P_{d,\min} = P_{r,\text{EOC}} \cdot \frac{d_r^2}{d_p^2} \quad (1c)$$

In Eq. (1), $P_{d,\min}$ is the minimum driving pressure, A_p is the cross-sectional area of the pneumatic piston, $P_{r,\text{EOC}}$ is the pressure in the reactor at the EOC (i.e. P_c), A_r is the cross-sectional area of the reactor piston, d_p is the diameter of the pneumatic piston, and d_r is the diameter of the reactor piston.

The minimum driving pressure is such that the piston does not rebound at the EOC due to pressure on the reactor piston. So that the driving pressure can be much lower than the EOC pressure, the diameter ratio of the reactor piston to the driver piston is 2:5, allowing the driving pressure to be lower than the EOC pressure by a factor of 6.25. The actual driving pressure should exceed the minimum by some safety margin so that the reactor remains at constant volume even if there is some pressure rise due to heat release in the reaction chamber prior to the main ignition.

There is not a theoretical upper limit on the driving pressure. It is desired that the piston should reach the EOC conditions in as short a time as possible to minimize heat loss from the reactants to the reactor walls and minimize the time for reactions to occur during the compression stroke. This implies that the driving pressure should be made as high as possible so that the highest piston velocity is achieved. However, higher piston velocities require a higher deceleration at the EOC. In the present RCM, the deceleration is provided by venting the hydraulic oil between steps on the hydraulic piston and matched steps on the front of the hydraulic chamber. If the piston is overdriven—that is, the driving pressure is too high—the piston will not be sufficiently decelerated

by the oil venting and will impact the front of the hydraulic chamber at high velocity. This can damage the RCM and cause the piston to rebound elastically. It also generates substantial noise in the pressure trace and should be avoided.

Typical driving gas pressures are between 50 psi for $P_C = 15$ bar experiments to 125 psi for $P_C = 50$ bar experiments. These driving pressures represent a good compromise between the minimum required for no rebound at EOC due to pressure and no rebound at EOC due to elastic reaction. Nonetheless, a small amount of piston rebound can be expected during/after the main ignition event. This small rebound may have an effect on the computation of ignition delay if it reduces the pressure rise rate during the ignition; it is expected that this effect will be very small relative to the typical random uncertainty in ignition delay experiments. Moreover, the driving pressures required to balance the full pressure rise during ignition are more likely cause elastic rebound, especially for high P_C when the post-ignition pressure rise is greater.

The EOC conditions (P_C and T_C) can be independently varied. This is made possible by independent variation of the compression ratio, initial pressure and initial temperature, and the specific heat ratio of the test gases. The compression ratio can be increased by adding spacers onto the rear of the hydraulic chamber or increasing the stroke, and can be reduced by adding split shims onto the rear of the reaction chamber or increasing the EOC clearance length. Adjustment of the specific heat ratio of the gas can be accomplished by substituting components (e.g. substituting Ar for N₂ results in higher P_C and T_C if all other conditions are fixed). The initial temperature is controlled by heaters, as described in the following section.

0.1.2 Test Gas Mixture Preparation

Fuel/oxidizer pre-mixtures are prepared in two mixing tanks, one approximately 17 L and the other approximately 15 L in volume. These large volumes allow many runs to be conducted from one mixture preparation. The mixing tanks are connected to the reaction chamber by flexible stainless steel manifold tubing. The tanks, reaction chamber, and connecting manifold are wrapped in heating tape and insulation to control the initial temperature of the mixture. Temperature controllers from

Omega Engineering use thermocouples placed on the lid of each mixing tank, approximately in the center of each mixing tank, embedded in the wall of the reaction chamber, and near the inlet valve of the reaction chamber to control the preheat temperature of the mixture. A static pressure transducer measures the pressure in the manifold and mixing tanks. This transducer is used during mixture preparation and to measure the initial pressure of a given experiment. Two transducers are used for various experiments in this work, as described below in Sec. 0.1.8.2.

Most of the fuels studied in this work are liquids at room temperature and pressure and have relatively low vapor pressure. A similar procedure, outlined below, was used for all of the butanol isomers, *iso*-pentanol, and methylcyclohexane; specific procedures are given in the chapter relevant to each fuel. First, the mixing tanks are vacuumed to an ultimate pressure less than 5 torr. The liquid fuel is massed in a syringe to a precision of 0.01 g prior to injection through a septum. Proportions of O₂, N₂, and Ar are added manometrically at room temperature. The preheat temperature of the RCM is set above the saturation point for each fuel to ensure complete vaporization. The vapor pressure as a function of temperature is calculated according to fits taken from Yaws [19]. A magnetic stirrer mixes the reactants. The temperature inside the mixing tank is allowed to equilibrate for approximately 1.5 h.

This approach to mixture preparation has been validated in several previous studies by withdrawing gas samples from the mixing tank and analyzing the contents by GC/MS [20], GC-FID [3], and GC-TCD [7]. These studies have verified the concentration of *n*-butanol, *n*-decane, and water, respectively. In addition, both the work by Kumar et al. [3] on *n*-decane and the study of Weber et al. [20] on *n*-butanol confirmed that there was no fuel decomposition over the course of a typical set of experiments. Furthermore, each new mixture preparation is checked against previously tested conditions to ensure reproducibility.

0.1.3 Definition of Ignition Delay

The pressure in the reaction chamber during an experiment is monitored by a Kistler 6125B piezoelectric dynamic pressure transducer. The charge signal from the transducer is amplified and converted

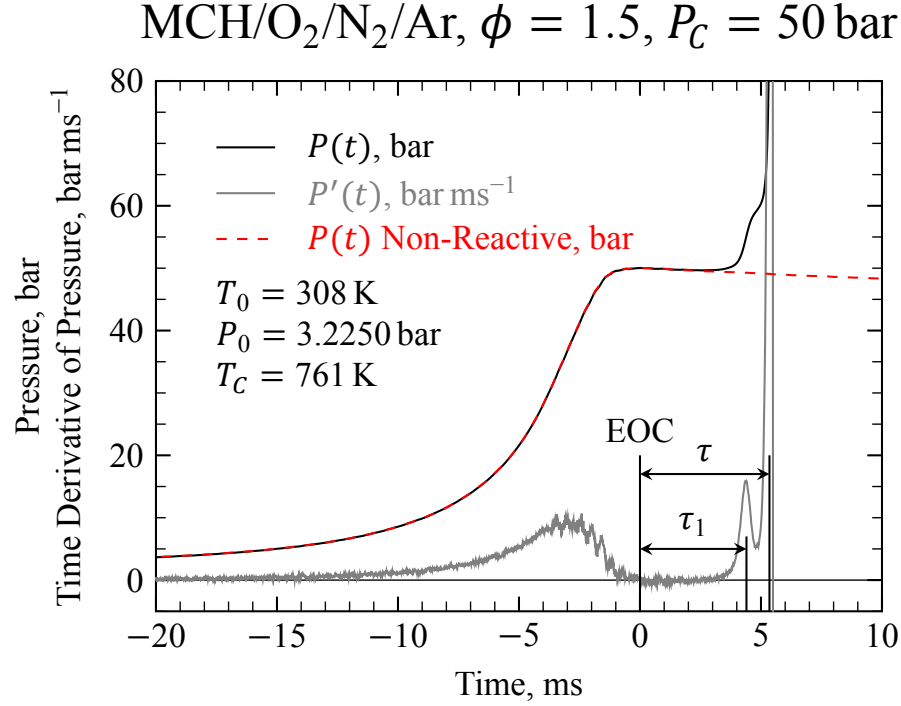


Figure 3: Representative pressure trace indicating the definition of the first stage and overall ignition delays and the corresponding non-reactive pressure trace. EOC stands for End of Compression.

to a voltage by a Kistler 5010B charge amplifier. The voltage is sent to a National Instruments cDAQ equipped with the NI-9215 module. The signal is recorded by a LabView VirtualInstrument at 50 kHz.

Figure 3 shows a representative pressure trace from these experiments with methylcyclohexane (MCH) at $P_c = 50 \text{ bar}$, $T_c = 761 \text{ K}$, and $\phi = 1.5$ (See ??). Note that Fig. 3 shows a case with two stages of ignition; not all of the fuels studied had conditions that showed two-stage ignition. Nonetheless, the ignition delay is consistently defined in all the work in this study. The definitions of the EOC and the ignition delays are indicated on the figure. The end of compression time is defined as the time when the pressure reaches its maximum before first stage ignition occurs, or for cases where there is no first stage ignition, the maximum pressure before the overall ignition occurs. The first stage ignition delay is the time from the end of compression until the first peak in the time derivative of the pressure. The overall ignition delay is the time from the end of compression until the largest peak in the time derivative of the pressure.

Each unique P_C and T_C condition is repeated at least 5 times to ensure repeatability of the experiments. The experiment closest to the mean of the runs at a particular condition is chosen for analysis and presentation. The standard deviation of all of the runs at a particular condition is less than 10 % of the mean in all cases. The uncertainty of the ignition delay at each condition is estimated as twice the standard deviation of all the runs at a particular condition.

0.1.4 Non-Reactive Experiments

Figure 3 also shows a representative non-reactive pressure trace corresponding to the experimental conditions in the figure. Due to heat loss from the test mixture to the cold reactor walls, the pressure and temperature of the gas in the reaction chamber will decrease after the end of compression. A non-reactive pressure trace is measured that corresponds to each unique P_C and T_C condition studied to quantify the effect of the heat loss on the ignition process and to verify that no heat release has occurred during the compression stroke. The non-reactive pressure trace is acquired by replacing the O_2 in the oxidizer with N_2 , so that the specific heat ratio of the initial mixture is maintained, but the heat release due to exothermic oxidation reactions is eliminated. Maintaining a similar specific heat ratio ensures that the non-reactive experiment faithfully reproduces the conditions of the reactive experiment.

0.1.5 Reaction Chamber Homogeneity

An RCM to be used for studies of homogeneous chemistry—as in this study—must ensure that homogeneous conditions exist inside the reaction chamber for the duration of the experiment. Due to the high piston velocities required to minimize heat loss and reaction during the compression stroke, complex fluid mechanical effects can strongly affect the state of the reactants at the EOC. The most important of these effects is caused by the motion of the piston itself, where the piston pushes the wall boundary layer into a roll-up vortex [21]. This cold vortex mixes with the hotter gases near the center of the reaction chamber and causes large spatial inhomogeneities of temperature and species.

To facilitate spatially homogeneous conditions in the reactor and reduce the effect of the roll-up vortex, it is necessary to trap the boundary layer. This is accomplished in the present RCM by a crevice machined into the crown of the piston, shown in cross-section in Fig. 4. The boundary layer enters the crevice through the converging section as the piston moves forward and is trapped within the crevice. The dimensions of the crevice were optimized by Mittal [2] through computational fluid dynamic (CFD) simulations. Subsequently, Mittal and Sung [22] experimentally showed that the optimized crevice design provided homogeneous conditions in the reaction chamber up to approximately 150 ms after the EOC. By using planar laser induced fluorescence (PLIF) measurements of acetone-seeded mixtures, Mittal and Sung [22] showed that there was a core region of gases near the center of the reactor whose temperature remained spatially homogeneous.

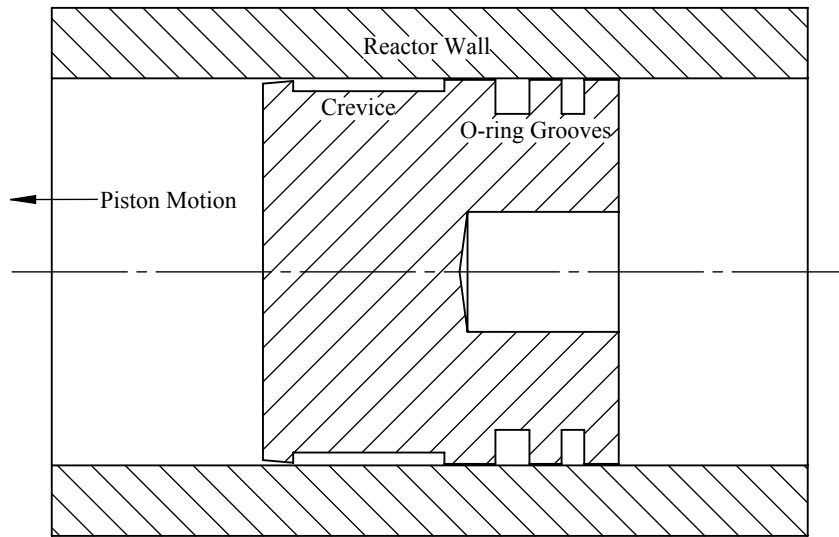


Figure 4: Creviced piston installed in the present RCM.

0.1.6 Determination of Reactant Temperature

In general, it is rather difficult to directly measure the temperature of the gases in the reaction chamber during and after compression. Intrusive methods such as thermocouples may introduce

inhomogeneities into the reaction chamber and non-intrusive optical techniques are difficult to set up and require extensive calibration at the pressures of interest in RCM studies. Thus, the temperature is determined indirectly by applying an assumption called the “adiabatic core hypothesis” to the reaction chamber [1, 21].

If all of the gases in the reaction chamber were compressed isentropically, the temperature at the end of compression could be found by the following relations:

$$\ln(\text{CR}) = \int_{T_0}^{T_{ic}} \frac{1}{T(\gamma - 1)} dT \quad (2a)$$

$$\ln\left(\frac{P_{ic}}{P_0}\right) = \int_{T_0}^{T_{ic}} \frac{\gamma}{T(\gamma - 1)} dT \quad (2b)$$

where CR is the volumetric compression ratio, T_0 is the initial temperature, T_{ic} is the temperature at the end of isentropic compression, γ is the temperature-dependent ratio of specific heats, P_{ic} is the pressure at the end of isentropic compression, and P_0 is the initial pressure.

However, experiments have shown that the measured pressure in the reaction chamber does not reach the value of P_{ic} calculated by using the geometric compression ratio. The difference is due to finite heat loss from the reactants to the reactor walls and the crevice volume during the compression. Under the adiabatic core hypothesis, it is assumed that the heat loss from the reactants only occurs in a thin boundary layer near the wall, and the central core region is unaffected by heat loss (i.e. the core is adiabatic) [23]. Thus, the heat loss is modeled as an effective reduction in the compression ratio, and the temperature during the compression stroke can be calculated by:

$$\ln\left(\frac{P_C}{P_0}\right) = \int_{T_0}^{T_C} \frac{\gamma}{T(\gamma - 1)} dT \quad (3)$$

where P_C is the measured pressure at the end of compression, T_C is the temperature at the end of compression, and the other variables are the same as in Eq. (2).

After the end of compression, the pressure in the reaction chamber decreases, as can be seen in Fig. 3. This pressure decrease is caused by heat loss from the reactants in the constant volume

reaction chamber and is accompanied by a decrease in the temperature of the reactants. To model the thermodynamic state after the end of compression, the adiabatic core hypothesis is applied and the heat loss is assumed to occur only in a thin boundary layer near the reactor walls. Thus, the core region is modeled as adiabatic, and the heat loss from the boundary layer is modeled as an isentropic volume expansion.

In general, the specific heat ratio used in Eqs. (2) and (3) is an unknown function of temperature and composition, so Eq. (3) cannot be integrated directly to find T_C . If the specific heats are parameterized with a linear fit and the composition is assumed to be fixed, it is possible to integrate Eq. (3) directly, but this process is quite tedious; nonetheless, it will be applied in Sec. 0.1.8 to determine the uncertainty of T_C . In general, the simplest method of calculating T_C is to use software to numerically integrate Eq. (3).

In this work, the CHEMKIN-Pro [24] software is used to perform the numerical integration and calculation of T_C . The CHEMKIN-Pro software provides the facility for a user-specified volume profile as a function of time to be applied to a homogeneous, adiabatic reactor. Since the adiabatic core of the reaction chamber is modeled as undergoing an isentropic volumetric compression followed by an isentropic volumetric expansion, this user-specified volume functionality is used to compute the RCM reactor state as a function of time in CHEMKIN-Pro.

A volume trace for simulation is computed from the measured pressure trace using the isentropic relation:

$$\frac{V_2}{V_1} = \left[\frac{P_1}{P_2} \right]^{\frac{1}{\gamma}} \quad (4)$$

where V_1 and V_2 are the volumes at consecutive time points, P_1 and P_2 are the pressures at consecutive time points, and γ is the temperature dependent specific heat. This equation is applied during and after the compression stroke to calculate the volume trace. Since the non-reactive experiment requires slightly different initial pressure (typically on the order of 5 torr) to reach the same compressed pressure as the reactive experiment—due to the slightly different specific heat ratio in the non-reactive

experiment compared to the reactive experiment—the reactive pressure trace is used to compute the volume trace until EOC; after EOC, the corresponding non-reactive pressure trace is used. In Eq. (4) it is assumed that changes in composition of the reactants are negligible during the compression stroke, which is confirmed by comparing simulations with and without reaction steps in the chemical kinetic model. The EOC conditions are the same in both cases. The initial volume is arbitrarily taken to be equal to 1.0.

For use in Eq. (4), the temperature-dependent specific heat ratio γ is tabulated for each time point. Thus, the temperature at each time point must also be computed by using the isentropic relation for temperature:

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1} \right]^{\frac{\gamma-1}{\gamma}} \quad (5)$$

where T_2 and T_1 are the temperatures at consecutive time points. Since T_2 depends on the value of γ , which in turn depends on T_2 , Eq. (5) is iterated until the temperature changes by less than one tenth of one percent on consecutive iterations. Once again, it is assumed that changes in composition have a negligible influence on the ratio of specific heats. The temperature calculated by Eq. (5) is typically within 1K of the temperature calculated by CHEMKIN-Pro.

CHEMKIN-Pro expects the volume profile in a tabular format, with each row containing the volume at a specified time. For ease of import, the csv file format is used. Since the volume is computed at each point that the pressure is experimentally measured (i.e. at a rate of 50 kHz), every fifth volume point is selected for tabulation to reduce the computation time in CHEMKIN-Pro.

0.1.7 Numerical Methods

Two types of simulations are conducted using the Closed Homogeneous Batch Reactor in CHEMKIN-Pro [24]. The first type uses the tabulated volume profile and is specified in the CHEMKIN-Pro input file with the VPRO keyword. Therefore, this type of simulation is referred to as a VPRO simulation hereafter. The second type is a constant volume, adiabatic simulation and is referred

to as CONV hereafter, again named after the CHEMKIN-Pro input keyword used to specify this problem type. The CONV type simulations do not capture the effect of the compression stroke and post-compression heat loss; therefore, they allow direct analysis of the kinetic model with no influence of potentially confounding experimental effects.

As mentioned previously, VPRO simulations are used to calculate the temperature at the end of compression, T_C . This temperature is used as the reference temperature for reporting the ignition delay. Simulations to determine TC are conducted with and without detailed reaction steps to determine if there is significant reactivity in the compression stroke. If there is no significant reactivity (and hence heat release), the pressure and temperature at EOC are the same whether or not reactions are included in the simulation.

0.1.8 Uncertainty of Compressed Temperature

The uncertainty of the compressed temperature is an important parameter to report. Since T_C is not measured, we must perform an uncertainty propagation analysis on the equation used to calculate T_C , Eq. (3). First, we simplify the term involving γ in Eq. (3). By definition, γ is the ratio of the specific heat at constant pressure to that at constant volume:

$$\gamma \equiv \frac{C_p}{C_v} = \frac{C_p/R}{C_v/R} = \frac{\hat{C}_p}{\hat{C}_v} \quad (6)$$

where C_p and C_v are the specific heats in molar units at constant pressure and volume, respectively, and R is the universal gas constant, used to produce non-dimensional specific heats, indicated by a hat. The difference between the non-dimensional specific heats is one, $\hat{C}_v = \hat{C}_p - 1$. Then, it follows that:

$$\frac{\gamma}{\gamma - 1} = \frac{\frac{\hat{C}_p}{\hat{C}_v}}{\frac{\hat{C}_p}{\hat{C}_v} - 1} = \frac{\frac{\hat{C}_p}{\hat{C}_p - 1}}{\frac{\hat{C}_p}{\hat{C}_p - 1} - 1} = \frac{\frac{\hat{C}_p}{\hat{C}_p - 1}}{\frac{1}{\hat{C}_p - 1}} = \hat{C}_p \quad (7)$$

In Eq. (3), the total specific heat ratio for the mixture should be used; thus, the simplification as

shown in Eq. (7) requires that the specific heat \hat{C}_p also be the total specific heat. In the following, we assume that there is negligible change of the total specific heat due to changes in reactant mole fractions, as for Eqs. (4) and (5). The total specific heat is simply the sum of the product of the species mole fractions and their specific heats:

$$C_{p,\text{total}} = \sum_i X_i C_{p,i} \quad (8a)$$

$$\hat{C}_{p,\text{total}} = \frac{\sum_i X_i C_{p,i}}{R} \quad (8b)$$

where i indicates the species and X_i is the species mole fraction. In the NASA polynomial formulation used by CHEMKIN, the non-dimensional specific heat at constant pressure as a function of temperature is represented by a fourth-order polynomial fit:

$$\hat{C}_{p,i} = c_{1,i} + c_{2,i}T + c_{3,i}T^2 + c_{4,i}T^3 + c_{5,i}T^4 \quad (9)$$

In general, this means that the specific heat can be non-linear. However, since the mixtures prepared in this study are composed primarily of O₂, N₂ and Ar (i.e. no more than 7% of any mixture is the fuel), and since the specific heats of O₂, N₂ and Ar are only weakly temperature dependent over the range of temperatures experienced during compression, for the purposes of this uncertainty analysis, we will approximate the total specific heat as a linear function of temperature:

$$\begin{aligned} \hat{C}_{p,\text{total}} &= \sum_i X_i \hat{C}_{p,i} \\ &= \sum_i X_i \left(\sum_{j=1}^5 c_{j,i} T^{j-1} \right) \\ &\approx a + bT \end{aligned} \quad (10)$$

where a and b are found by fitting the total non-dimensional specific heat over the temperature range from 300 K to 1100 K, as discussed below in Sec. 0.1.8.4.

With this approximation of the specific heat, we can integrate Eq. (3) to find the compressed temperature:

$$\ln \frac{P_C}{P_0} = \int_{T_0}^{T_C} \frac{\gamma}{T(\gamma - 1)} dT \quad (11a)$$

$$= \int_{T_0}^{T_C} \frac{\hat{C}_p}{T} dT \quad (11b)$$

$$= \int_{T_0}^{T_C} \frac{a + bT}{T} dT \quad (11c)$$

$$= \left[a \ln T + bT \right]_{T_0}^{T_C} \quad (11d)$$

$$\ln \frac{P_C}{P_0} + (a \ln T_0 + bT_0) = a \ln T_C + bT_C \quad (11e)$$

Equation (11e) can be solved explicitly for T_C by using Lambert's W function [25], but this function is somewhat complex. Instead, Eq. (11e) is simplified by performing a Taylor expansion of the right hand side and solving for T_C :

$$a \ln T_C + bT_C \approx a \ln T_e + bT_e + \left(\frac{a}{T_e} + b \right) (T_C - T_e) \quad (12)$$

$$T_C = \frac{\ln \frac{P_C}{P_0} + a \ln \frac{T_0}{T_e} + b(T_0 - T_e)}{\frac{a}{T_e} + b} + T_e \quad (13)$$

where T_e is the temperature about which the Taylor expansion is performed.

With an explicit function for T_C , we can estimate the uncertainty in T_C by the quadratic sum of the uncertainty in the parameters in Eq. (13) multiplied by the partial derivative of Eq. (13) with respect to each of the parameters [26]. The parameters are P_C , P_0 , T_0 , a , and b and are assumed to be independent with normally distributed uncertainties.

$$U_{T_C} = \sqrt{\left(\frac{\partial T_C}{\partial P_C} U_{P_C} \right)^2 + \left(\frac{\partial T_C}{\partial P_0} U_{P_0} \right)^2 + \left(\frac{\partial T_C}{\partial T_0} U_{T_0} \right)^2 + \left(\frac{\partial T_C}{\partial a} U_a \right)^2 + \left(\frac{\partial T_C}{\partial b} U_b \right)^2} \quad (14)$$

In general, the uncertainties of each parameter may not be normally distributed and several of

the parameters are correlated (i.e. not independent), so the following analysis provides only an approximation of the true uncertainty. More detailed analysis (e.g. by a Monte Carlo method) is required to investigate the interactions of the uncertainties.

The uncertainties of the parameters, U_j in Eq. (14), are in general found by their own root square sum procedure:

$$U_j^2 = B_j^2 + R_j^2 \quad (15)$$

where the subscript j represents one of the parameters in Eq. (13). The total uncertainty of a particular parameter is composed of two parts, the systematic or bias uncertainty (B_j) and the precision or random uncertainty (R_j). In general, the bias uncertainty is contained in the measurement equipment and can be reduced, e.g. by using different equipment; the random uncertainty is inherent in any measured process and cannot be reduced by experimental techniques. The bias and precision uncertainties for each parameter will be discussed in the following sections.

The partial derivatives of Eq. (13) with respect to each of the parameters are given in Eq. (16):

$$\frac{\partial T_C}{\partial P_C} = \frac{T_e}{P_C (a + T_e b)} \quad (16a)$$

$$\frac{\partial T_C}{\partial P_0} = \frac{-T_e}{P_0 (a + T_e b)} \quad (16b)$$

$$\frac{\partial T_C}{\partial T_0} = \frac{T_e (a + T_0 b)}{T_0 (a + T_e b)} \quad (16c)$$

$$\frac{\partial T_C}{\partial a} = \frac{T_e \left[b \left(T_e \ln \frac{T_0}{T_e} + T_e - T_0 \right) - \ln \frac{P_C}{P_0} \right]}{(a + T_e b)^2} \quad (16d)$$

$$\frac{\partial T_C}{\partial b} = - \frac{T_e \left[a \left(T_e \ln \frac{T_0}{T_e} + T_e - T_0 \right) + T_e \ln \frac{P_C}{P_0} \right]}{(a + T_e b)^2} \quad (16e)$$

0.1.8.1 Uncertainty in Initial Temperature

The bias uncertainty in the initial temperature is due to the standard limits of error of the K-type thermocouple used to measure the initial temperature. According to the Omega Engineering specifications, this is “the greater of 2.2 °C or 0.75 %”. The largest initial temperature used in this work, 413 K, leads to an uncertainty of ± 3 K; thus, $B_{T_0} = 3$ K. Bias uncertainty due to the A/D converter in the process meter is negligible compared to this uncertainty. The precision uncertainty is due to the limit of precision of the display on the Omega Engineering CNi3254 process meter used to control the process temperature. This is ± 0.05 K. The total uncertainty of the initial temperature is:

$$U_{T_0} = \sqrt{(B_{T_0})^2 + (R_{T_0})^2} = \sqrt{(3 \text{ K})^2 + (0.05 \text{ K})^2} = 3 \text{ K} \quad (17)$$

0.1.8.2 Uncertainty in Initial Pressure

The bias uncertainty in the initial pressure is due to the standard error in the pressure transducer used to measure the initial pressure. Two different pressure transducers have been used in this study; the first, an Omega Engineering PX-303 (range: 0 psia to 50 psia), has a full scale uncertainty of 1.25 %, or ± 0.625 psi (4309.2 Pa). The second transducer is an Omega Engineering MMA100V10T2D0T4A6 type (range: 0 torr to 5200 torr) and was purchased because preliminary results of this uncertainty analysis indicated that the largest contributor to the uncertainty of T_c was the initial pressure measurement. The full scale uncertainty of the MMA type transducers is 0.05 %, resulting in an uncertainty of ± 2.6 torr (346.6 Pa), an order of magnitude lower than the PX-303 while also providing more than double the operating range. Total uncertainties using the appropriate pressure transducer are reported in each experimental section of this work; both transducers will be analyzed in this section. Bias uncertainty due to the signal acquisition equipment is negligible compared to the standard error in the pressure transducers.

The precision uncertainty is due to the limit of precision of the display on the Omega Engineering

DP41-B process meter used to monitor the initial pressure. This is ± 0.005 torr (0.666 Pa). The total uncertainty of the initial pressure is:

$$U_{P_0} = \sqrt{(B_{P_0})^2 + (R_{P_0})^2} = \sqrt{(4309.2 \text{ Pa})^2 + (0.666 \text{ Pa})^2} = 4309.2 \text{ Pa} \quad (18a)$$

$$U_{P_0} = \sqrt{(B_{P_0})^2 + (R_{P_0})^2} = \sqrt{(346.6 \text{ Pa})^2 + (0.666 \text{ Pa})^2} = 346.6 \text{ Pa} \quad (18b)$$

0.1.8.3 Uncertainty in Compressed Pressure

The bias uncertainty in the compressed pressure is due to the standard error in the piezoelectric pressure transducer. According to the manufacturer's calibration, the deviation of the full scale output from linearity is less than 0.1 % over the pressure range 0 bar to 50 bar, indicating that $B_{P_C} = 0.05 \text{ bar} = 5000 \text{ Pa}$. The uncertainties in the signal acquisition equipment are negligible compared to this uncertainty. The precision uncertainty is due to the limit of precision of the output of the pressure, and is $5 \times 10^{-7} \text{ bar}$. This is negligible compared to the bias uncertainty, so the total uncertainty of the compressed pressure is:

$$U_{P_C} = B_{P_C} = 0.05 \text{ bar} = 5000 \text{ Pa} \quad (19)$$

0.1.8.4 Uncertainty in the Specific Heat

The uncertainty in the specific heat comes from two sources. First is the uncertainty in the mixture composition and second is the uncertainty in the linear fit to the total specific heat. The uncertainty in the mixture composition can be estimated by the same method as is used for T_C . The specific heat is given by Eq. (8), so we can take partial derivatives of that equation with respect to the mole fractions of the species to find the total uncertainty:

$$\begin{aligned} (U_{\hat{C}_{p,\text{total}}})^2 &= \left(\frac{\partial \hat{C}_p}{\partial X_1} U_{X_1} \right)^2 + \dots + \left(\frac{\partial \hat{C}_p}{\partial X_n} U_{X_n} \right)^2 \\ &= (\hat{C}_{p,1} U_{X_1})^2 + \dots + (\hat{C}_{p,n} U_{X_n})^2 \end{aligned} \quad (20)$$

where n is the total number of species. In Eq. (20), it is assumed that the uncertainty in the specific heats of each species is negligible. This is considered an acceptable assumption for stable species such as the fuel molecules, oxygen, nitrogen, and argon. Experience with several kinetic mechanisms has shown that the typical variation in individual \hat{C}_p fits causes approximately 1 K changes in T_C .

The uncertainty of the mole fraction of the species is estimated differently depending on how the species was introduced to the mixing tank. For liquid fuel species, experiments with GC/MS have shown that there is approximately 5 % variation in mole fraction from the expected value [20]; this value is adopted for the total uncertainty of all liquid fuels. The mole fraction of the gaseous species is determined by their partial pressures when filling; the mole fraction is related to the pressure by Dalton's Law of Partial Pressure [27, 28]:

$$X_i = \frac{P_i}{\sum_i P_i} \quad (21)$$

where P_i is the partial pressure of a species and the sum is over all of the species. It follows that:

$$\begin{aligned} (U_{X_i})^2 &= \left(\frac{\partial X_i}{\partial P_i} U_{P_i} \right)^2 + \sum_{j \neq i} \left(\frac{\partial X_i}{\partial P_j} U_{P_j} \right)^2 \\ &= \left(\frac{\sum_{j \neq i} P_j}{(\sum_i P_i)^2} U_{P_i} \right)^2 + \sum_{j \neq i} \left(\frac{-P_i}{(\sum_i P_i)^2} U_{P_j} \right)^2 \end{aligned} \quad (22)$$

The uncertainties of each of the pressures P_i are equal and can be estimated by the same procedure as in Sec. 0.1.8.2 since the same pressure transducer is used to measure the pressure. It is assumed that the uncertainty in each partial pressure is independent of all the others for simplicity, although this will not strictly be the case because the gases are filled sequentially.

A line is fit through the end points of the total specific heat curve via simultaneous solution of the equations:

$$\begin{aligned} \hat{C}_{p,2} &= bT_2 + a \\ \hat{C}_{p,1} &= bT_1 + a \end{aligned} \quad (23)$$

where $\hat{C}_{p,1}$ and $\hat{C}_{p,2}$ are the total specific heats at T_1 and T_2 respectively. Solving Eq. (23) for b and a gives:

$$\begin{aligned} b &= \frac{\hat{C}_{p,2} - \hat{C}_{p,1}}{T_2 - T_1} \\ a &= \frac{f_2 \hat{C}_{p,2} - f_1 \hat{C}_{p,1}}{f_2 - f_1} \end{aligned} \quad (24)$$

where f_1 and f_2 are chosen so that b is eliminated in Eq. (23).

Uncertainty in the slope and y-intercept can be found by:

$$\begin{aligned} (U_b)^2 &= \left(\frac{\partial b}{\partial \hat{C}_{p,1}} U_{C_{p,1}} \right)^2 + \left(\frac{\partial b}{\partial \hat{C}_{p,2}} U_{C_{p,2}} \right)^2 \\ (U_a)^2 &= \left(\frac{\partial a}{\partial \hat{C}_{p,1}} U_{C_{p,1}} \right)^2 + \left(\frac{\partial a}{\partial \hat{C}_{p,2}} U_{C_{p,2}} \right)^2 \end{aligned} \quad (25)$$

where the partial derivatives are:

$$\frac{\partial b}{\partial \hat{C}_{p,1}} = \frac{-1}{T_2 - T_1} \quad \frac{\partial b}{\partial \hat{C}_{p,2}} = \frac{1}{T_2 - T_1} \quad (26)$$

$$\frac{\partial a}{\partial \hat{C}_{p,1}} = \frac{-f_1}{f_2 - f_1} \quad \frac{\partial a}{\partial \hat{C}_{p,2}} = \frac{f_2}{f_2 - f_1} \quad (27)$$

and the uncertainties of the specific heats $U_{C_{p,1}}$ and $U_{C_{p,2}}$ are calculated as described earlier.

0.1.8.5 Uncertainty in Compressed Temperature for Alcohol Experiments

The following analysis is conducted for a mixture of 3.38 mol % *t*-butanol, 20.30 mol % O₂, and 76.32 mol % N₂, i.e. a $\phi = 1.0$ mixture of *t*-butanol and air. Similar results are obtained for experiments with the other butanol isomers and *i*-pentanol and experiments at different fuel concentrations, because the fuel specific heats are similar and each experiment uses similar diluent concentrations.

A typical total pressure after filling is approximately 1520 torr (202,650 Pa), with approximately 42,000 Pa of O₂ and 160,650 Pa of N₂. The partial pressure of the liquid fuel is assumed to contribute

a negligible amount to the total pressure during the filling of the gases for the purposes of this uncertainty analysis. The results shown below use the uncertainty associated with the PX-303-type pressure transducer because this transducer was used for all of the experiments with alcohol fuels.

Applying Eq. (14) to typical conditions of $P_0 = 500$ torr to 760 torr, $T_0 = 300$ K to 400 K, and $P_C = 15$ bar to 30 bar yields a maximum uncertainty of approximately 2 % to 3 % of the compressed temperature T_C .

0.1.8.6 Uncertainty in Compressed Temperature for Methylcyclohexane Experiments

The following analysis is conducted for a mixture of 1.05 mol % MCH, 10.99 mol % O₂, 12.83 mol % N₂, and 75.13 mol % Ar, i.e. the stoichiometric mixture (#1) from ???. Similar results are obtained for the other mixtures.

A typical total pressure after filling is approximately 3390 torr (452,000 Pa), with approximately 33,500 Pa of O₂, 78,200 Pa of N₂, and 340,300 Pa of Ar. The partial pressure of the liquid fuel is again assumed to contribute a negligible amount to the total pressure during the filling of the gases for the purposes of this uncertainty analysis. The results shown below use the uncertainty associated with the MMA-type pressure transducer because this transducer was used for all of the experiments with MCH.

Applying Eq. (14) to typical conditions of $P_0 = 500$ torr to 1520 torr, $T_0 = 300$ K to 400 K, and $P_C = 15.1$ bar to 50 bar yields a maximum uncertainty of approximately 1 % of the compressed temperature T_C .

0.2 Rapid Sampling Apparatus

The Rapid Sampling Apparatus (RSA) used in this study is an adaptation of the RSA described in the work of Mittal and Sung [1] and Mittal [2]. The basic concept is the same as that developed by Roblee [29]. An polyester-film diaphragm is punctured by a pointed rod at the appointed time,

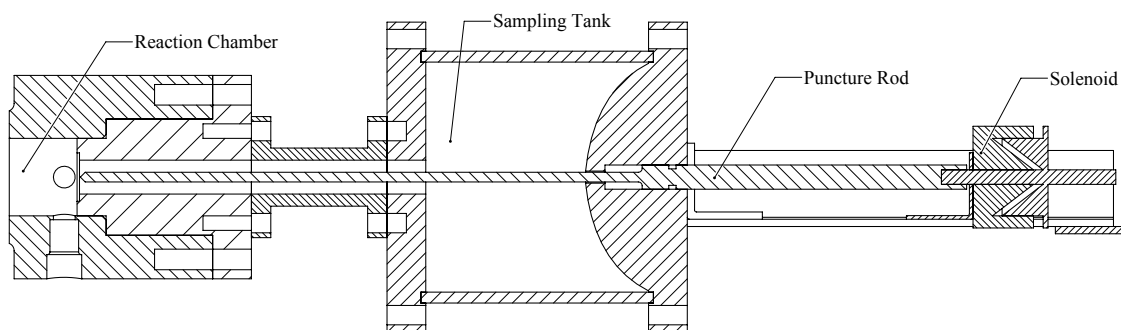


Figure 5: Schematic of the modified RSA used in this study

evacuating the contents of the reaction chamber into a large vessel. The temperature drop caused by the expansion of the gases into the sampling chamber quenches the reactions, and the products can be removed to an analysis system.

The design of Mittal [1, 2] used an electromagnet to hold a spring in compression. At the designated sampling time, the power to the electromagnet was cut, and the spring force thrust the puncture rod forward into the diaphragm. This system was prone to premature puncture if the spring force overcame the electromagnetic force (e.g. due to a small drop in the current to the electromagnet).

To alleviate the premature puncture problem, the puncture mechanism has been updated as shown in Fig. 5. The electromagnet/spring system has been replaced with a linear-acting solenoid. The puncture rod is held in the retracted position by a permanent magnet (not shown) to overcome the pressure force acting on the cross section of the rod when the sampling tank is under vacuum. At the sampling time, the solenoid is actuated by a DC voltage to puncture the diaphragm.

Figure 6 shows a pressure trace from the reaction chamber when the solenoid has been triggered (red, black) and a pressure trace when the solenoid is not actuated (blue). It can be seen that there is a very rapid drop in pressure in the reaction chamber when the diaphragm is ruptured. In the case with ignition, the diaphragm is ruptured purely by the pressure differential between the reaction chamber and the sampling tank. In the other two cases, the puncture rod breaks the diaphragm and the pressure differential evacuates the reaction chamber gases into the sampling tank.

The ratio of the EOC volume of the reaction chamber to the total (approximate) volume of

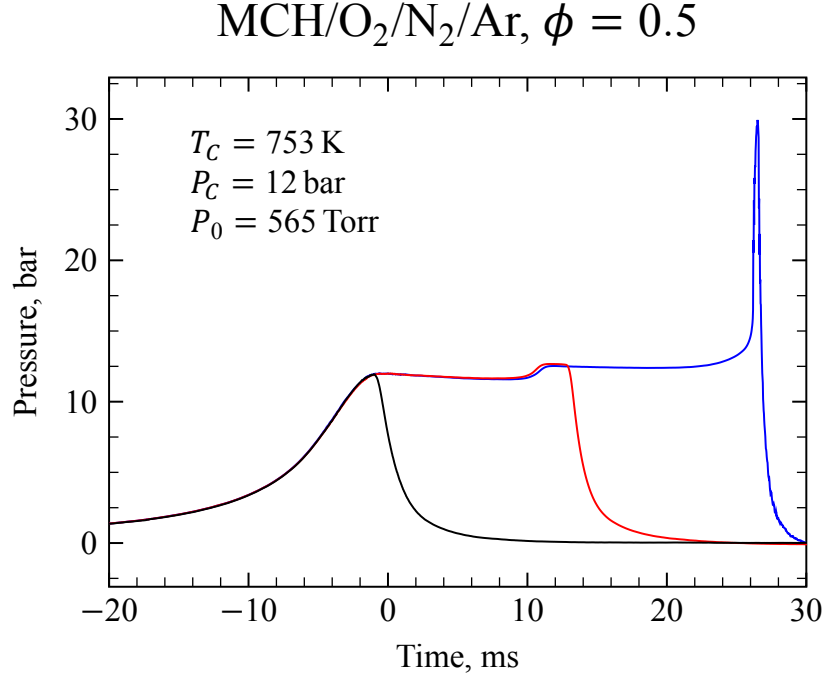


Figure 6: Pressure traces of representative experiments utilizing the rapid sampling apparatus. Blue: rupture due to ignition. Red and Black: rupture due to puncture rod.

the sampling tank plus the reaction chamber is 1.1772×10^{-2} . Assuming the expansion into the sampling tank is isentropic and the ratio of specific heats is fixed at $\gamma = 1.3$, the temperature ratio is approximately 2.6379×10^{-1} , leading to temperatures after expansion on the order of $T \approx 200$ K, depending on T_C . After expansion, the gases are warmed to room temperature. The fuel partial pressure in the sampling tank is a factor of two lower than the saturated vapor pressure at room temperature, so that heating of the sampling tank is not required.

The sampled gases are removed from the sampling tank by a gas-tight syringe through a septum. The syringe is equipped with a pressure lock so that the barrel of the syringe can be closed to the atmosphere after the sample is withdrawn. In addition, closing the barrel of the syringe allows the sampled gases to be pressurized for injection into the gas chromatograph by pushing on the plunger. He et al. [30] used a similar procedure in their experiments, and compared results using a heated syringe and an unheated syringe. They found that excellent agreement between results with the heated and unheated syringes; since a similar procedure is used in these experiments, an unheated syringe is used as well.

0.3 Gas Chromatograph/Mass Spectrometer

0.3.1 Theory of Gas Chromatography/Mass Spectrometry

0.3.1.1 Gas Chromatography

A gas chromatograph (GC) is a device that physically separates components of a gas sample by means of a tube—known as a *column*—lined or filled with a substance that interacts with the components in the sample. The sample is transported the length of the column by a flow of carrier gas, usually helium or hydrogen, also known as the *mobile phase*. A detector is placed at the outlet of the column to measure the amount and type of components eluted from the column.

The separation of the gaseous components in the sample is effected by the interaction of the sample with the lining of the column, known as the *stationary phase*. Gaseous species that have little interaction with the stationary phase and spend most of their time in the mobile phase are eluted from the column before species that interact strongly with the stationary phase and spend little time in the mobile phase [31].

The column is placed in an insulated oven so that its temperature may be controlled. The column temperature in a given analysis may be constant or may be controlled as a function of time. Since the time that a given component takes to move through the column is a function of temperature, this facility allows optimization of the elution time of the various components in the sample.

The injector of the GC is also temperature controlled; the temperature of the injector is set high enough so that all components (including the solvent, if any) are vaporized but not so high that the sample starts to degrade. On the present GC, a split/splitless injector is installed. This allows for operation in the split mode, where a percentage of the injected sample is removed from the injector prior to injection onto the column, or in the splitless mode, where nearly all of the sample is injected into the column. The split mode is used in this work. The amount of sample removed is controlled

by a valve in the injector. The split ratio is calculated according to Eq. (28):

$$\text{Split Ratio} = \frac{\text{Column Flow} + \text{Vent Flow}}{\text{Column Flow}} \quad (28)$$

where the column flow is the carrier gas flow rate at the head of the column and the vent flow is the flow out of the splitter vent [31].

0.3.1.2 Mass Spectrometry

Many types of detectors are available for GC analyses. These commonly include flame ionization detectors, thermal conductivity detectors, and mass spectrometers. In this work, a mass spectrometer is used to identify and quantify the species eluted from the column.

The fundamental operation of a mass spectrometer (MS) is to detect the spectrum of ions in a given sample. The MS generates this spectrum by detecting the mass-to-charge (m/z) ratios of the ions. Ions are generated from the effluent of the column—which includes sample components, mobile phase, and column bleed, collectively called *analytes*—by an ionization source, typically either electronic or chemical in nature. Nearly all of the ions generated will have a single charge, $z = 1$ [32]; thus, the m/z value of the ions is also equal to the mass of the ion.

In this work, electron ionization (EI) is used to generate the ions for analysis. The effluent from the column is passed in front of an electron source so that the electrons impact the analyte molecules and remove an electron, generating a positive ion. EI is a *hard ionization* technique, in that the electron impact transfers a significant amount of energy to the analyte molecule [32]. The additional energy causes the ion to fragment into two or more pieces; the spectrum of these fragments is characteristic for a given molecule and can be used as a “fingerprint” to identify the source molecule for a given spectrum.

After ionization, the fragments are formed into a beam and accelerated out of the ionization chamber towards the detector. Several detectors are available, including time-of-flight and transmission quadrupole. All of these detectors require high vacuum to avoid impact of the ion beam with

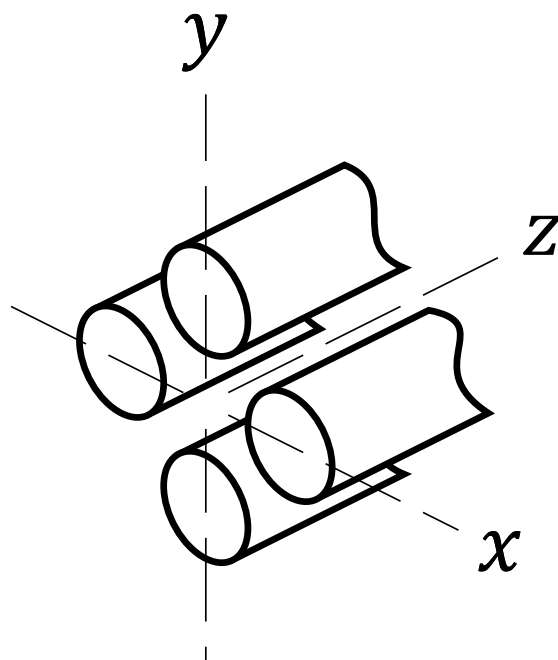


Figure 7: Schematic of the transmission quadrupole in an MS.

extraneous species prior to reaching the detector. The vacuum is achieved in the present MS by a two-stage design, using a rotary vane pump in combination with a turbomolecular pump to achieve ultimate pressures of approximately 2 Pa.

The MS used in this study is a transmission quadrupole type, shown schematically in Fig. 7. The transmission quadrupole separates specific ions from the ion beam by means of a time-varying electric field. Conceptually, the quadrupole can be imagined as four round rods, arranged in a cross pattern, with their long axes aligned parallel to the ion beam (i.e. the z axis). The ions are admitted to the rods at one end (e.g. at the origin in Fig. 7) and the detector is placed parallel to the $x - y$ plane in Fig. 7 at the other end of the rods (not shown in Fig. 7). A positive DC voltage is applied to one pair of the rods, while a negative DC voltage is applied to the other pair of rods; in addition, an AC voltage is applied simultaneously to all four rods. Assuming a specific ratio of AC amplitude to DC amplitude, ions of a certain m/z will remain in the ion beam and reach the detector. Then, holding the AD:DC amplitude ratio fixed, the amplitudes are ramped with a known function of time. This varies the particular m/z that will remain in the ion beam and reach the detector to be recorded [32], generating a mass spectrum.

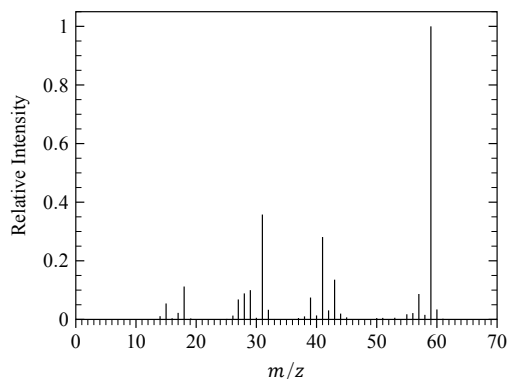


Figure 8: Example mass spectrum for a given scan during a GC/MS analysis

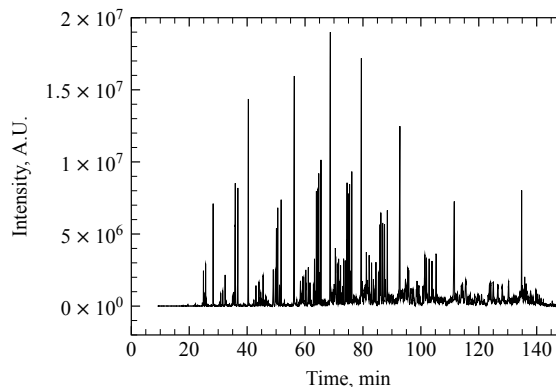


Figure 9: Example TIC for a GC/MS analysis of Jet Fuel

The voltage amplitudes are ramped many times per second—typical ramp times range from 0.05 s to 0.5 s, depending on the range of m/z values to be acquired—so that many spectra are acquired during the elution of a given chemical compound from the column, which typically occurs on the order of a few seconds. For a given scan from the lowest to the highest amplitude, the number of ions of each m/z is measured at the detector. This information is typically presented in the form of a relative intensity plot. The abscissa is the (integer) m/z while the ordinate is the intensity of a particular m/z scaled by the maximum intensity of all the m/z in a given scan. It is not required that the m/z be integers, although they are usually presented as such for simplicity. An example of a mass spectrum for a given time in a GC/MS analysis is shown in Fig. 8.

In addition to the mass spectrum, the MS reports the total ion current (TIC), also known as the total ion chromatogram. This is the sum of all of the mass intensities for a given scan. A sample TIC is plotted in Fig. 9 where the abscissa is time in min and the ordinate is an arbitrary unit. Finally, the MS can also report the mass chromatogram (MC), which is the chromatogram for a specific m/z as a function of time.

0.3.2 Identification of Species using GC/MS

Species are identified using a GC/MS system by their unique mass spectra. Each peak in the TIC typically represents one compound eluting from the column, although in theory each peak can

Table 1: GC/MS Method Parameters

Name	Value
Column Flow Rate	0.98 mL min ⁻¹
Purge Flow Rate	3.0 mL min ⁻¹
Linear Velocity	19.7 cm s ⁻¹
Split Ratio	100 : 1
Column Temperature	50 °C
Injector Temperature	200 °C
Interface Temperature	200 °C
Ion Source Temperature	200 °C
Ionization Voltage	0.73 kV for 8 min; 0.83 kV for 27 min
Scan Interval	0.11 s
Scan Range	10 Da to 150 Da
MS Threshold	100

represent more than one compound if the compounds are retained similarly by the column. The peak is caused by an increase in the number of ions reaching the detector on each scan relative to the baseline as the compound elutes and is ionized. As mentioned previously, many scans of the desired m/z range are conducted over the time that a compound is eluting from the column. To determine the identity of a compound in a given peak, the set of mass intensities over the peak are averaged and the background spectrum is subtracted; this average spectrum is compared to a database supplied by the National Institute of Standards and Technologies (NIST). The database returns several suggested species with a degree of matching parameter indicating how well the supplied spectrum matches the spectrum in the database.

0.3.3 Experimental Procedure

The GC/MS used in this study is a Shimadzu model QP-2010S, equipped with a split/splitless injector, as mentioned previously. The column used is a Restek RTX-1PONA capillary column with length 100 m, inner diameter 0.25 mm, and film thickness of 0.5 μ m. The carrier gas is helium with 99.9999 % purity. The operating parameters of the GC/MS (known as the *method*) are shown in

Table 1.