

Flame Propagation in Blends of R-152a, R-134a, and R-1234yf with Air¹

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Abstract

Some new, low-global warming potential refrigerants will be flammable, and the laminar burning velocity is a useful parameter for quantifying fire risk. Laminar burning velocity measurements have been made using a constant volume experiment with dry air and the refrigerant R-152a (CH_3CHF_2), pure and blended with R-134a (CH_2FCF_3), or R-1234yf (CF_3CFCH_2). The resulting burning velocity data deduced from the pressure rise in the chamber are presented for a range of fuel air equivalence ratio and loading of the less flammable refrigerant, for unburned gases at 298 K and 101 kPa as well as at 375 K and 253 kPa. For comparison, the 1-D, planar laminar burning velocity was numerically simulated using a recently developed kinetic mechanism that includes a wide range of refrigerants with air. The predicted burning velocities agree reasonably well with the experimental values, and the numerical results are used to understand the kinetic mechanism of the reaction of the refrigerants. Uncertainties in the experimental data from radiation heat losses as well as extrapolation to ambient conditions are explored.

Keywords: refrigerant flammability, R-152a, R-134a, R-1234yf, laminar flame speed, burning velocity, premixed flame.

1. Introduction

Existing, widely used hydrofluorocarbon (H)refrigerants have high global warming potential (GWP) and are significant sources of greenhouse gases in the atmosphere. As discussed by Velders et al. (2012), the increase in radiative forcing by HFCs between 2012 and 2050 is projected to be in the range of 14 % to 27 % of the increase due to CO_2 . Hence, as stipulated in the Kigali Agreement to the Montreal Protocol (UNEP, 2016), HFC use is being phased down, which has led to development of new low-GWP alternative refrigerants (Kujak and Sorenson, 2018). Unfortunately, the changes to the molecules to increase reactivity in the troposphere (use of alkenes and increase of hydrogen substitution), make the compounds more flammable (Kujak, 2017). In order to obtain the desired performance properties, blends are being used and, as has been done in the past (Domanski et al., 2021), the blends are optimized for the simultaneous requirements of thermodynamic efficiency, volumetric capacity, heat transfer, and low toxicity. Recently, flammability has been added as a parameter in the optimization (Kujak and Schultz, 2016), and while simple methods for screening purposes have been developed based on the heat of combustion (McLinden et al., 2017) and the adiabatic flame temperature and fluorine to hydrogen ratio (Linteris et al., 2019), a better metric is desirable.

The laminar burning velocity is a suitable metric for flammability. It is a fundamental combustion parameter that can be calculated from first principles, is correlated with quenching diameter, lean flame extinction, minimum ignition energy, and overall chemical rate, and it is used as a scaling parameter for turbulent flame speeds and as an input to full-scale explosion models. It is also used as a metric in existing and developing codes and standards for refrigerant flammability (ASHRAE, 2019, ISO, 2017).

The goal of the present work is to provide experimental data on the laminar burning velocity of R-152a ($\text{CHF}_2\text{-CH}_3$, 1,1-difluoroethane) and its blends with R-134a ($\text{CF}_3\text{-CH}_2\text{F}$, 1,1,1,2-tetrafluoroethane) or R-1234yf (CH_2CFCH_2 , 2,3,3,3-tetrafluoropropene) useful for kinetic mechanism development. A constant volume, spherically expanding flame experiment is employed in which the burning velocity is obtained from the pressure rise. The work illustrates the performance of a recently developed kinetic mechanism for refrigerant flammability and discusses data reduction considerations for these compounds in the present experiment. Data for combustion of R-134a and R-1234yf with air are also important since they are important blend components and their burning velocities are too low to measure on their own (at normal gravity).

The required chemical kinetic models for describing the combustion of HFC refrigerants with air are under development (Linteris and Babushok, 2020, Babushok et al., 2021a, Babushok et al., 2021b) based on earlier models of HFC compounds used as fire suppressants in hydrocarbon-air flames (Burgess Jr et al., 1995a, Burgess Jr et al., 1995b, Babushok et al., 2012). Recently, a kinetic mechanism has been developed (Babushok et al., 2021b) for use with the refrigerants R-32, R-125, R-134a, R-152a, R-143, R-143a, R-1234yf, R-1234ze(E), R-1243zf and their mixtures with air. A recent report (Babushok et al., 2021b) describes the validation of the mechanism which was done using available burning velocity data in the literature, most of which were from Takizawa and co-workers. These experimental burning velocity data were obtained primarily for screening purposes and safety code classification. The experiments mostly employed spherically expanding flames (SEFs) via the constant volume method (CVM) (Takizawa et al., 2005, Takizawa et al., 2006b, Takizawa et al., 2006a, Takizawa et al., 2008, Bennett, 2011, Moghaddas et al., 2014, Burrell et al., 2019a) in which the pressure rise is converted to the burning velocity via a thermodynamic model. Nonetheless, the data reduction did not account for radiation heat losses or the effects of the increasing pressure and temperature in the experiment on the equilibrium product distribution, which may be important for R-32/air flames (Burrell et al., 2019a). For a few refrigerants, data were also available from experiments using SEFs and the constant pressure method (CPM) (Takizawa et al., 2013b, Hegetschweiler et al., 2020) in which high-speed schlieren imaging of the flames provides the change in flame radius in time, from which the laminar burning velocity is obtained, and from experiments with upwardly-propagating flames in vertical tubes and optical imaging of the propagating flame (Clodic and Jabbour, 2011, Takizawa et al., 2013a, Papas et al., 2017).

More recently, experimental burning velocity data have been obtained primarily for kinetic model validation, for which corrections for stretch and radiation are required (Burrell et al., 2019a, Hegetschweiler et al., 2020, Hesse et al., 2021, Hegetschweiler et al., 2022). The present work expands upon earlier modeling work with the one-carbon HFC R-32 (CH_2F_2) (Burgess Jr et al., 2022) to now consider two-carbon compounds R-152a and R-134a, as well as the three-carbon compound R-1234yf. The purpose of the present work is to provide new experimental data to validate the mechanism for larger refrigerant molecules. For R-152a specifically, previous work includes measurements of burning velocity with the constant volume method by Takizawa et al. (2006), Moghaddas et al. (2014), and Burrell et al. (2019b). The present work provides new data for R-152a in which the effects of radiation heat losses on the data reduction are considered and extends the work to blends of R-152a with two other compounds, R-134a and R-1234yf, which have burning velocities too low to measure in the present apparatus as pure fuels with air (Burrell et al., 2019b, Takizawa et al., 2009). In reduction of the experimental data, the available pressure-time $P(t)$ data are typically cropped to eliminate the effects of ignition and stretch at early times, and wall disturbances at late times, and then extrapolated back to ambient conditions. This procedure has recently been explored for numerically generated pressure rise data. Using experimental data, the present work systematically quantifies the effects of data cropping on the inferred burning velocity using data for which ignition disturbances and flame acceleration are significant.

2. Experiments

2.1 Apparatus and Procedure

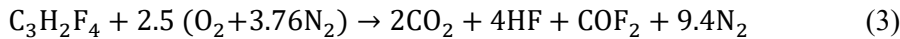
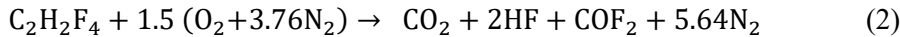
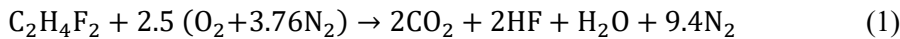
The experimental device is the same as reported previously (Pagliaro et al., 2015, Pagliaro et al., 2016b, Burrell et al., 2019a) and is described briefly here for convenience. A 1.85 L stainless steel spherical vessel is equipped with spark electrodes, an absolute pressure transducer, a dynamic pressure sensor, and a thermocouple. A vacuum pump reduces the pressure below 0.8 torr prior to reactant addition. The partial pressure of each reactant is determined using an absolute pressure transducer (Omega PX811-030AV) with a stated accuracy of $\pm 0.1\%$ that is periodically recalibrated using an MKS Baratron 627D absolute pressure transducer with a stated accuracy of $\pm 0.1\%$. In the present experiments, an external stainless steel bellows

pump circuit was added to mix the reactants for 2 minutes (80 air changes) before each test. Following this mixing, reactants are allowed to settle for 5 minutes prior to ignition. Two vertical opposing tungsten electrodes (0.4 mm diameter and a 2 mm gap) and a variable high voltage D.C. power supply produce a spark of energy that is within an order of magnitude of the minimum of that for ignition. In separate experiments, the minimum ignition energy (for stoichiometric conditions) was determined by increasing the ignition energy until sustained reaction occurred. Estimated minimum ignition energies (based on the energy stored in the capacitor) for R-152a/R-134a mixtures were 2.5 mJ, 12.5 mJ, and 56.3 mJ for fuel molar ratios of 100/0, 80/20, and 50/50, respectively. For all experiments, ignition was only attempted once for each mixture; if ignition did not occur, the mixture was purged, a fresh mixture prepared, the ignition energy increased, and the experiment repeated. Repeated ignition attempts were not made for a single gas preparation to avoid the possibility of partial reaction of the initial mixture.

A dynamic pressure sensor (PCB 101A06, claimed accuracy of 0.07 kPa) measures the pressure rise and a data acquisition system (National Instruments NI USB-6259) and related LabVIEW program records the pressure at 5000 Hz. After each test run, the product gases are quickly purged with high-pressure N₂ for 10 seconds followed by an air purge for 5 minutes, and then two cycles of vacuum and air purge for 2 minutes each. These serve to remove corrosive acid gases and reduce heating of the chamber by the combustion products. The initial temperature of the chamber, measured by a fine type-K thermocouple on the chamber exterior wall, was typically 298 K $\pm$ 2 K.

The reactant gases are R-152a (Honeywell), R-134a (Allied Signal, Genetron 134a) and R-1234yf (Honeywell). The air is house compressed air (filtered and dried) which is additionally cleaned by passing it through an 0.01 μ m filter, a carbon filter, and a desiccant bed to remove small aerosols, organic vapors, and water vapor. The humidity of the dry shop air has a dew point of -20°C, and this was verified using an approach reported previously (Pagliaro et al., 2016b). Experiments were performed over a fuel-air equivalence ratio of $\phi = 0.8$ to 1.4, with pure R-152a as the fuel, or its blend with R-134a (80/20 and 50/50 molar fractions) or with R-1234yf (50/50, 40/60, and 30/70), respectively. The highest fraction of the less flammable component was selected to keep the lowest burning velocity above about 5 cm/s. This was done to avoid the complications due to buoyancy, since Takizawa et al. (2013b) found that for stoichiometric and rich R-32/air flames, the pressure trace in constant volume experiments was the same for normal vs. microgravity conditions when the burning velocity > 5 cm/s.

The stoichiometric concentrations of the reactants are determined as described previously (Linteris et al., 2019). For pure R-152a, R-134a, and R-1234yf in dry air, the stoichiometric reactions are approximated by:



where the molar coefficient on the air, γ_i , is found to be 2.5, 1.5, and 2.5, respectively. These products have been found to be good approximations to those calculated at equilibrium for adiabatic conditions (Linteris et al., 2019). For the mixtures, the stoichiometric reaction is given by:

$$1 \text{ fuel} + \Gamma [\text{O}_2 + 3.76\text{N}_2] \quad (4)$$

in which the molar oxygen requirement Γ is given by the mole fraction x_i weighted stoichiometric air requirement of the constituents

$$\Gamma = \sum_{i=1}^{N_{\text{Comp}}} x_i \gamma_i \quad (5).$$

2.2 Data Reduction

The primary data from the experiment are the pressure as a function of time $P(t)$ from the dynamic pressure transducer. As the experiment progresses, the pressure P and temperature T increase due to isentropic compression of the unburned gases at radii larger than the flame radius R_f . Hence, a single experiment provides the burning velocity over a range of P and T . To obtain the burning velocity at a particular pressure/time from the pressure rise data, a thermodynamic model is used to relate the burned gas mass fraction y_b at each time to the pressure. In the thermodynamic model, a reaction sheet between burned and unburned gas zones is assumed to be smooth, spherical, and infinitely thin, and both the burned and unburned gases are treated as ideal. The unburned gas is assumed quiescent and is isentropically compressed as the flame expands, and chemical equilibrium is reached immediately after the gas is burned. Buoyancy is assumed to be negligible. In previous work (Burrell et al., 2019b), a two-zone thermodynamic model has been used, based upon the work of Metghalchi and Keck (1980) and Hill and Hung (1988). The present work employs a recently developed (Hegetschweiler and Linteris, 2021) and validated (Hegetschweiler et al., 2023) data reduction tool CVDART (Constant Volume Data Reduction Tool) for constant volume experiments. This tool allows various methods of solution to be applied as selected by the user, including a two-zone model based on the work of Metghalchi and Keck (1980) (but employing Cantera (Goodwin et al., 2016) as the thermodynamic solver), or two different multi-zone models, based on the work of Elia et al. (2000) or Xiouris et al. (2016). One advantage of the multi-zone models is that the effects of thermal radiation heat losses from the burned gases can be included, since the final temperature in the burned gases and the equilibrium state can be a function of R_f , unlike the two-zone model in which the burned gas composition is uniform throughout. In the current version of CVDART, an optically thin radiation model is employed. Another advantage of the multi-zone formulations is that changing burned gas temperature and equilibrium composition due to the isentropic compression of the burned gases, or due to radiation cooling, can be captured.

In the present work, the two-zone model is first applied to allow consistent comparisons with the inferred burning velocity of R-152a from earlier work (Takizawa et al., 2006b, Takizawa et al., 2006a, Burrell et al., 2019b), which also used a two-zone model. The kinetic model which is used in the present work for predicting the burning velocities was developed based on available data in the literature, which mostly has been obtained with a two-zone thermodynamic model. So in some sense, comparing the model predictions with experimental data reduced using a two-zone model would be consistent with the data used for its development. Nonetheless, all comparisons in the present paper between numerical predictions of burning velocity and our experimental data are made using experimental data reduced with a multi-zone model. The multi-zone modeling is performed by employing both the adiabatic model (ADI) and the optically thin radiation model (OTM) to assess the role of radiation in the present experiments and to allow comparison with the burning velocity obtained from data reduction using the two-zone model. Although it is not known a priori if radiation in the experiment is closer to adiabatic or optically thin, these two cases likely bound the behavior. Ultimately, more detailed narrow-line models of radiation would be desirable as have been performed previously for hydrocarbon flames (Grosshandler, 1993).

2.3 Extrapolation to Ambient Conditions

As described above, a single test run in the constant volume experiment provides data on the burning velocity at all temperatures and pressures along an isentrope. For screening purposes and use of the results as input to fire models, however, the burning velocity at 298 K and 0.101 MPa are typically desired. While experiments are typically initiated at conditions near laboratory ambient, ignition disturbances render data at early times unusable. Thus, data at 298 K and 101 kPa are typically obtained via an extrapolation to ambient from the higher T/P data. As described by Keck and co-workers (1982), power-law and Arrhenius functions have proven to be suitable. To provide more data and reduce the uncertainty of the extrapolation,

data are typically collected at three initial pressures P_i , providing three curves (isentropes), to which a power-law surface is fit of the form:

$$S_u = S_u^0 \left(\frac{T_u}{T_i} \right)^a \left(\frac{P}{P_i} \right)^b \quad (6)$$

where T_u and P are the unburned gas temperature and pressure, S_u is the laminar burning velocity, S_u^0 is a fitting parameter that represents the laminar burning velocity at initial conditions (T_i , P_i), and the exponents a and b are fitting parameters for the temperature and pressure dependence. Figure 1 (Burrell et al., 2019b) illustrates the surface fit to data at three initial pressures. In the present study, each case for a particular value of ϕ was tested at three initial conditions, (298 K, 88.9 kPa), (298 K, 101 kPa), and (298 K, 115.5 kPa), and S_u^0 at that value of ϕ was obtained as a parameter of the surface fit in Eq. (6). Data are cropped to cut out ignition disturbances and wall effects as well as instabilities from cellular flame formation. The effect of the data cropping for the present data are systematically evaluated in section 4.2 below.

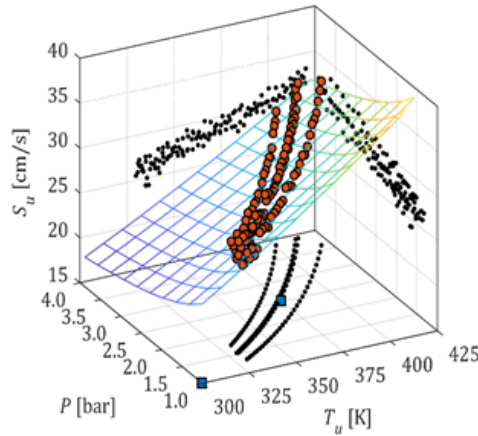


Figure 1 - Experimental curves (red dots) of burning velocity S_u as a function of unburned gas temperature T_u and pressure P , together with the surface fit from Eq. (6) for R-152a/air mixtures at $\phi=1.1$ from reference (Burrell et al., 2019b). Black dots are the projection of the data to the relevant plane. Experimental data have been cropped prior to the curve fit to reduce ignition and wall effects.

2.4 Uncertainties

Uncertainties in the experimental measurements have been described previously (Pagliaro et al., 2015, Pagliaro et al., 2016a). The uncertainties in experimental burning velocity are reported as expanded uncertainties $U = k u_c$ determined from a combined standard uncertainty u_c and a coverage factor $k = 2$ corresponding to a level of confidence of 95%. The combined standard uncertainty is determined using the root-sum-of-squares (RSS) method of combining individual uncertainty components. As described by Chen (2015), uncertainties in the initial conditions can be propagated to uncertainties in the burning velocities. Using his estimations based on numerical modeling, uncertainties in the initial temperature, pressure, mixture equivalence ratio, and concentration of more highly fluorinated fuel, of 3 K, 1.3 kPa, 1%, and 0.3% result in a maximum expanded relative uncertainty of about 10 % in S_u^0 , which occurs at lean conditions when the uncertainty in the equivalence ratio has the largest effect on the reported data. Of course, these uncertainties do not include those from stretch effects, radiation heat losses or extrapolation to ambient conditions (and the required data cropping), which are discussed below.

3. Numerical Simulations

In the present work, laminar burning velocity calculations are made with Python scripts employing Cantera (Goodwin et al., 2016), an open-source suite of object-oriented software tools for problems involving chemical kinetics, thermodynamics, and transport processes. The equations of mass, species, and energy conservation are solved numerically for the initial gas compositions, temperature, and pressure corresponding to those in the experiments. The solution assumes isobaric, adiabatic, steady, planar, one-dimensional, laminar flow and neglects the Dufour effect but includes thermal diffusion. Molecular diffusion is modeled with the multi-component transport equations using the Hirschfelder approximation. The boundary conditions, corresponding to a freely propagating flame, are inlet mass fractions, velocity and temperature, and vanishing gradients downstream from the flame. The number of active grid points was selected to assure that the solutions were grid independent.

3.1 Kinetic Model

The kinetic model is that of Babushok et al. (Babushok et al., 2021b), developed specifically to predict the burning velocity of C_1 , C_2 , and C_3 hydrofluorocarbon HFC refrigerants with air at ambient conditions, for which experimental data are available in the literature. The mechanism has 1064 reactions with 113 species, and was developed based on earlier NIST mechanisms for HFC flame suppressants (Burgess Jr et al., 1995a, Babushok et al., 2012, Linteris et al., 2012); the Naval Research Laboratory flame suppression reactions for R-227ea (Williams et al., 2000); the NIST mechanism for flame suppression by 2-bromo-3,3,3-trifluoropropene (2-BTP) (Babushok et al., 2015, Burgess et al., 2015), which is a bromo-substituted fluoropropene; and the model for the decomposition of 2,3,3,3-tetrafluoropropene, 1,3,3,3-tetrafluoropropene, 3,3,3-trifluoropropene (Babushok et al., 2021a, Babushok and Linteris, 2017). The mechanism can also account for increased initial temperature and pressure typical of the present experiments.

4. Results

4.1 Experimental Data

The experimental pressure rise data for R-152a/air mixtures for the various values of ϕ are shown in Figure 2. Equivalent figures for all the R-152a/R-134a and R-152a/R-1234yf fuel mixtures are provided in the Supplementary Materials. As indicated in Figure 2 for R-152a, lower data cropping at about $1.5P_0$ to $1.8P_0$ is used, as described in more detail below. For the upper limit, the maximum pressure is limited to less than half of the peak pressure rise for lean mixtures, but much less than that as ϕ increases. Hence, only part of the pressure rise data are usable. The reasons for this are illustrated in Figure 3 which shows the laminar burning velocity S_u which is extracted from the pressure rise data using the thermodynamic model (Hegetschweiler and Linteris, 2021), as a function of pressure. As illustrated, at low pressure, the flame is over-driven from the ignition energy and there are oscillations (perhaps from the ignition process or electrical noise) and hence cropping of the data is required. At higher pressure, abrupt changes in slope, likely due to formation of cellularity in the flame, which is more important for richer flames, require cropping of the data at pressures well below that of the inflection point in the $P(t)$ data. While the present figures are used to illustrate the behavior, the selection criteria for the cropping bounds as well as the effects of cropping bounds on S_u are discussed in more detail below. Such plots of S_u vs. P for all of the refrigerant blends in the present paper are presented in the Supplementary Materials.

Using the data ranges indicated in the figures, as well as the equivalent data for slightly higher and lower initial pressures as described in section 2.3 above, the power-law curve-fits are then used to extrapolate S_u to ambient conditions (298 K, 101 kPa). Note in Figure 3 that the S_u data at the initial conditions cannot be

used due to both the over-driven nature of the ignition process (yielding slightly higher initial values of S_u) and the oscillations in the data at early times. Burning velocity data² at ambient conditions from the extrapolations (e.g., Eq. (6)) as a function of ϕ for R-152a/air mixtures are given in Figure 4 along with data from Burrell et al. (2019b) and Takizawa et al. (2006b, 2006a). While recent work (Hegetschweiler et al., 2023) has shown that multi-zone models are more accurate than two-zone models, the data in Figure 4 are nonetheless reduced using the two-zone model so that a proper comparison can be made with the results of Takizawa et al. (2006b, 2006a), and Burrell et al. (2019b), who also used a two-zone model. As indicated, the present data agree with those of Burrell et al. (2019b) very closely, but they are up to about 8 % lower than those of Takizawa et al. (2006b, 2006a) for lean conditions. The reasons are unknown, but may be related to the data cropping, as described below. Nonetheless, this difference is well within the uncertainty of the two experiments. Similar comparisons for mixtures of R-152a with R-134a at volume fractions of 0.80/0.20 and 0.50/0.50 are shown in Figure 5. The dashed lines in this figure are cubic fits to the experimental data, not model predictions. As indicated, with added R-134a, the present data show a lower peak value of the burning velocity (by 10 % to 15 %) than the results of Takizawa et al., and a value of ϕ for the peak at about $\phi=1.1$ for all R-152a/R-134a mixtures, as opposed to ϕ_{peak} of about 0.95, 1.0, and 1.1 for 1.00/0.00, 0.80/0.20, and 0.50/0.50, respectively, for Takizawa's data. Also, with addition of the less flammable HFC, the present burning velocities are significantly higher for rich flames and significantly lower for lean flames than those of Takizawa et al. (2006b). The reasons for these discrepancies are unknown; however, we tend to believe our data for the following reason. In Figure 5, the leanest data point ($\phi=0.8$) of Takizawa et al. (2006b) for the R-152a/R-134a blends at 100/0 and 80/20 molar ratios have nearly the same burning velocities. This is highly unexpected since replacing 20% of the flammable R-152a with the non-flammable or R-134a is very unlikely to yield nearly the same burning velocity. It should also be noted that Takizawa et al. (2006b) mention in their paper that for the hard-to-ignite conditions, they used a different ignition system, with an ignition energy higher by a factor of ten from the other flames. This may have lead to over-driven flame propagation and higher measured burning velocities for those flames with added R-134a under lean conditions (typically harder to ignite).

² Tables of the burning velocity data are presented in the Supplementary Material.

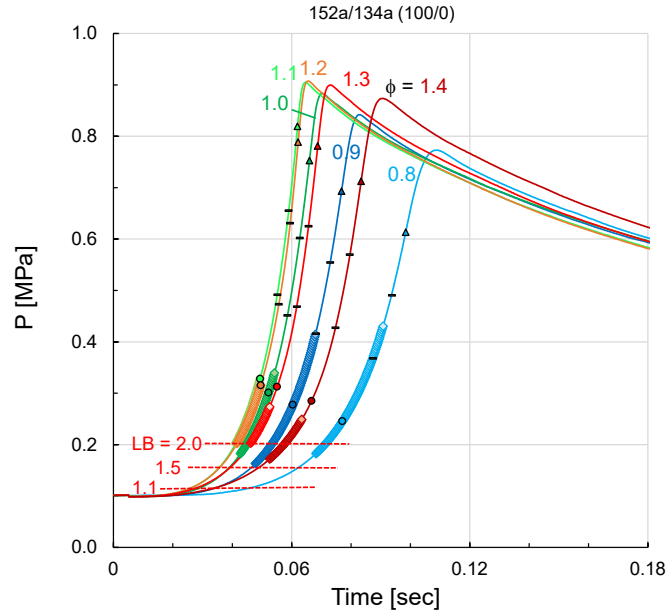


Figure 2 - Dynamic pressure in the chamber as a function of time for R-152a/air mixtures. Each curve refers to the indicated value of ϕ . Lower bounds for data cropping are given by the red dotted lines at the bottom, corresponding to the specific multiplier of P_0 : 1.1, 1.5, and 2.0. The upper bounds are indicated as specific fractions of P at the inflection point: 0.4, 0.6, 0.8, 1.0, given by the symbols $\circ$, $\square$, $\triangle$, and Δ , on each curve, respectively. Data actually used for the power-law curve fits for extrapolation to ambient conditions are given by the open, colored symbols on each curve.

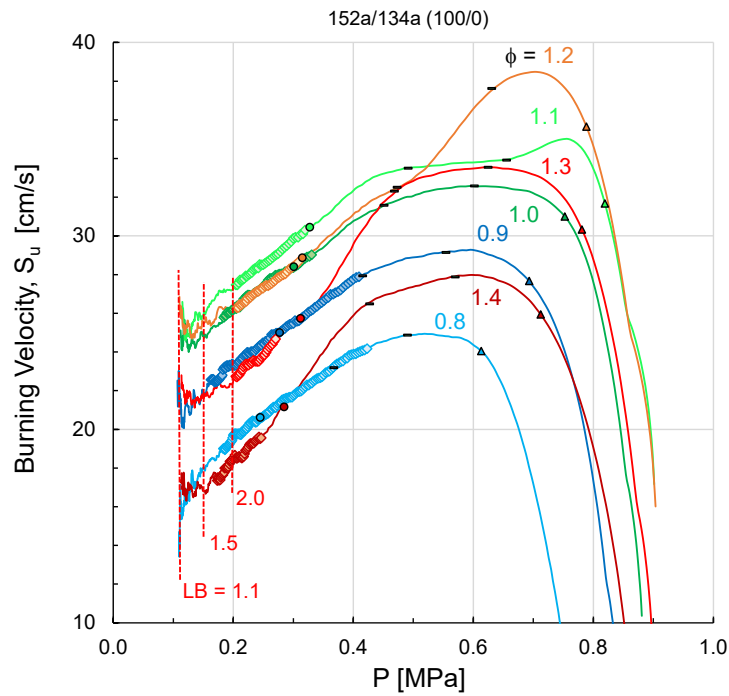


Figure 3 - Experimental burning velocity as a function of pressure for R-152a/air mixtures. Each curve refers to the indicated value of ϕ . Data cropping bounds and data keys are as in Figure 2.

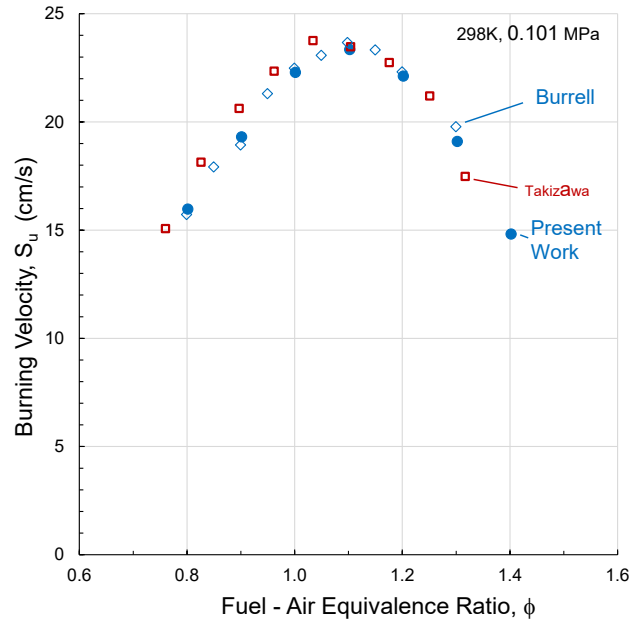


Figure 4 – Experimental burning velocity as a function of ϕ for R-152a/air mixtures at 298 K, 0.101 MPa initial conditions (i.e., from extrapolation using the power-law fit). All experimental data are reduced with a two-zone thermodynamic model: ●, present data; Δ , Burrell et al. (2019b); $\square$, Takizawa et al. (2006b, 2006a).

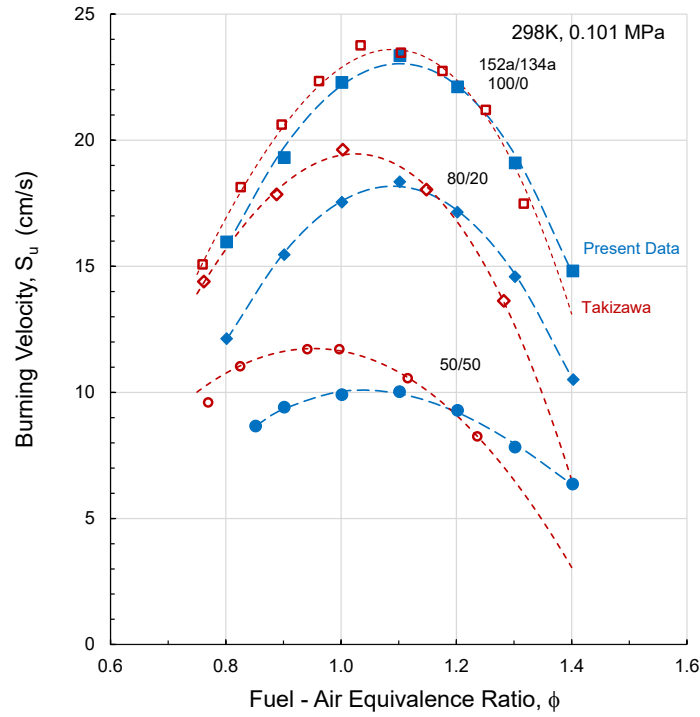


Figure 5 - Experimental burning velocity as a function of ϕ for air with R-152a/R-134a mixtures at volume fractions of 100/00, 80/20, and 50/50, at 298 K, 101 kPa initial conditions (from extrapolation using the power-law fit). All experimental data are reduced with a two-zone thermodynamic model: ●, blue closed circles, present data; □, red open squares, Takizawa et al. (2006b, 2006a). Dashed lines are cubic fits to the experimental data.

In Figure 4 and Figure 5, the two-zone model was used in the data reduction process to facilitate comparisons between the present data and those in the literature for the same conditions. For comparison to numerical modeling predictions, however, it is more appropriate to use a multi-zone model with and without radiation heat losses.

Figure 6 and Figure 7 show, for mixtures of R-152a with increasing amounts of R-134a or R-1234yf, respectively, the burning velocity as a function of ϕ . The numerical predictions are shown by the lines (dashed lines: OTM radiation; solid lines: adiabatic (ADI), no radiation), and the experimental data are shown by the symbols (open: data reduction assuming OTM radiation; closed: ADI, no radiation). The left frames in the figures are for ambient conditions 298 K, 101 kPa (i.e., from extrapolation using the power-law fit) and the right, for elevated T and P (375 K, 253 kPa). For most of the conditions of the present flames, the effect of OTM radiation in the planar simulations is very small. Radiation does become more important, reducing the burning velocity by up to 15% for the flames having added R-134a or R-1234yf (i.e., slower flames) and under rich conditions (for which the concentrations of radiating species are higher). For pure R-152a (top sets of curves, either figure), the numerical results for ambient conditions are very close to the experiments reduced using the OTM assumption, while at the elevated temperature they are close to those of the ADI assumption. The left frame of Figure 6 also shows the experimental results of Moghaddas et al. (2014) for pure R-152a as the long-dashed line (it is the curve fit to their experimental data as given in that reference). Their data were reduced using a multi-zone model that accounts for radiation heat losses; the peak burning velocity is about 8 % lower than the present data reduced with the OTM radiation model and has a maximum at $\phi=1.2$ as opposed to 1.1 for the present data. With added R-134a, numerical results for both temperature cases are close to ADI for the 80/20 mixture, and somewhat below the ADI for the 50/50 mixtures. With added R-1234yf, all numerical results are close to the ADI assumption for all mixtures and temperatures, except for those of the richer 50/50 mixtures for which the numerical results drop off faster than do the experiments. While there is moderate disagreement in the present plots, the performance is still considered good since these are the first such comparisons for R-134a in a pure refrigerant/air flame, and only the second data for R-1234yf. It should also be noted that while the relevant rate parameters in the mechanism were adjusted (within their uncertainties) to provide the best agreement possible, the mechanism was also required to predict burning velocities of a large number of other refrigerants/air mixtures as well as hydrocarbon/air/refrigerant (i.e., inhibitor) mixtures. An interesting result is that the model performance is relatively consistent between the extrapolated results to ambient and those directly measured at higher T/P , implying that the extrapolation is not the cause of the discrepancy.

An important observation for all mixtures is that while the effects of radiation in the simulations is relatively mild, selecting the correct radiation condition is very important for the reduction of pressure rise data to obtain burning velocity. This result has been verified in recent work in which synthetically generated pressure rise data from direct numerical simulations of time-dependent spherical flames was used as input to the data reduction schemes (Hegetschweiler et al., 2023). In that work, the numerical simulations were performed both with and without optically thin radiation. If the correct radiation model was then employed in the reduction of the pressure rise data, the burning velocity was very accurately deduced; if the incorrect radiation model was employed, the inferred burning velocity showed significant errors, as in the present work.

As shown in Figure 6 and Figure 7, the inferred burning velocity from the pressure rise data depends significantly on the radiation model applied in the data reduction. For pure R-152a at 298 K, 101 kPa

(Figure 6, left frame, top curves), OTM data reduction compared to ADI leads to burning velocities about 5 % to 8 % higher (depending upon ϕ), and for R-152a/R-134a at 50/50 molar ratio (bottom curves), 12 % to 15 % higher.

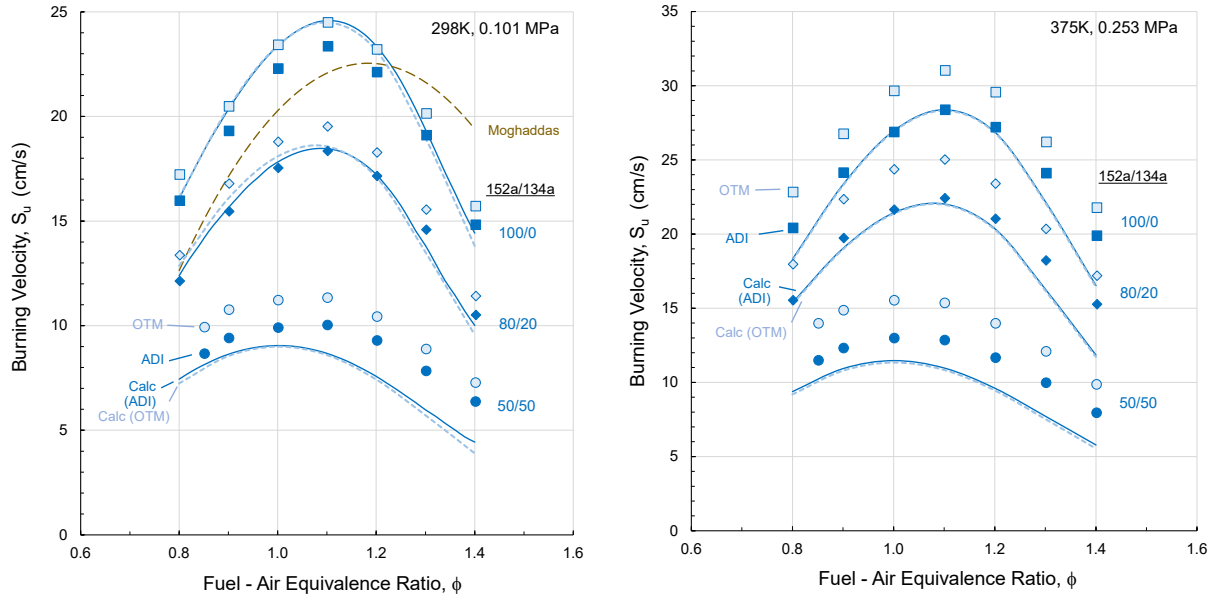


Figure 6 – Experimental (symbols) and numerically predicted (lines) burning velocity as a function of ϕ for R-152a/R-134 mixtures at volume fractions of 100/00, 80/20, and 50/50, and 298 K, 101 kPa initial conditions.

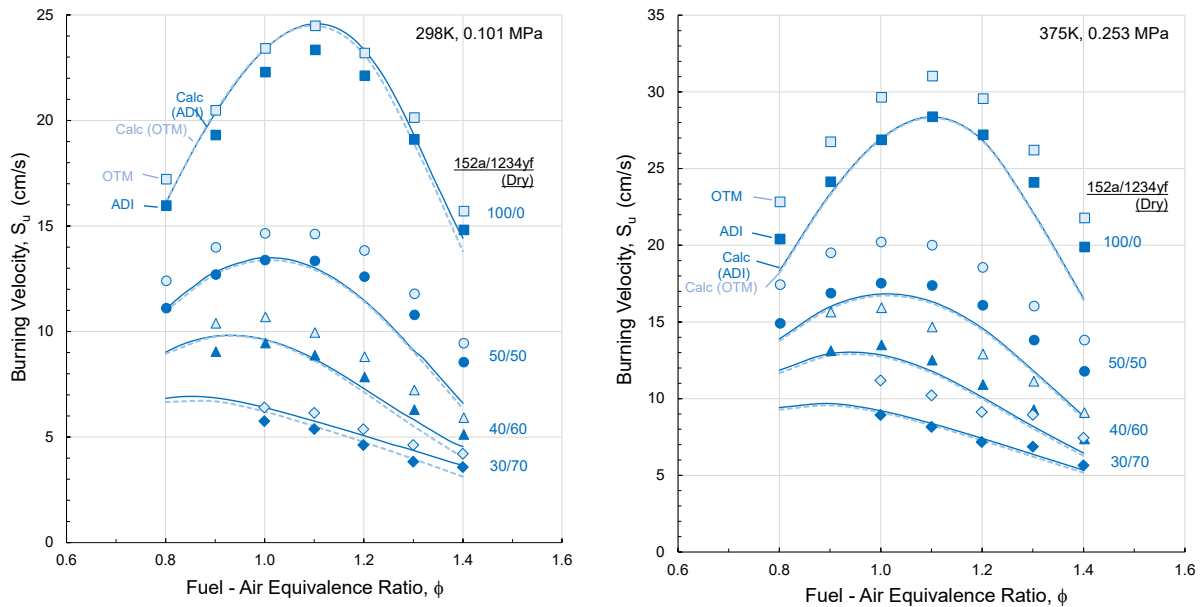


Figure 7 - Experimental (symbols) and numerically predicted (lines) burning velocity as a function of ϕ for R-152a/R-1234yf mixtures at volume fractions of 100/00, 50/50, 40/60, and 30/70 and 375 K, 253 kPa initial conditions.

4.2 Effect of Data Cropping

As described above, the range of usable experimental data is limited by physical effects such as ignition disturbances, wall heat losses, and transition to cellular flames. Cropping of the experimental $P(t)$ data prior to the extrapolation curve fit can help to isolate data most useful for determining laminar burning velocity at the initial conditions. Following approaches adopted in the literature (Takizawa et al., 2008, Takizawa et al., 2013b, Moghaddas et al., 2014, Omani and Tartakovsky, 2016, Davis et al., 2017), the lower and upper cropping limits are determined by visually examining the curves of $S_u(P)$ as in Figure 3 (not $P(t)$ data). In Figure 3, a good curve for illustration purposes is that at $\phi=1.4$. At the low end, the oscillations in the data at early times (as well as any overdriven propagation enhanced by the ignition energy) can be eliminated by selecting a lower cropping limit of $1.7P_0$; at about $P = 0.25$ MPa, there is a sudden increase in the burning velocity, likely due to formation of cellular flames, and an upper bound of 0.25 MPa appears appropriate. The inflection point in the pressure rise curve is indicated by the triangular symbols on each curve (Figure 2 and Figure 3); for $\phi=1.4$, it occurs at about 0.71 MPa, so that the upper cropping limit is about 0.35 times the pressure at the inflection point. Note that the open symbols on each curve fit illustrate the data range actually used for the curve fitting and for the extrapolation.

Table 1 presents the lower and upper cropping limits adopted for all mixtures for each value of ϕ . The lower cropping limits were generally in the range of $1.5P_0$ to $2.0P_0$. Note that this is somewhat lower than the value of $2.0P_0$ suggested in recent numerical work for R-32/air flames (Hegetschweiler et al., 2023), based on stretch considerations; however, as illustrated in Figure 8 and Figure S-3 discussed below, for the present flames, the effect of increasing the lower bound from $1.5P_0$ to $2.0P_0$ is small, always less than 2 %, except for some of the richer flames for which it can be up a 5 % effect. This cannot be avoided for the rich flames, however, since due to flame acceleration, there is very little data available between the two bounds, as discussed below. The suggested upper cropping limits vary between 0.3 and 0.75 times the pressure at the inflection point. While these selected values seem reasonable, the question naturally arises as to how different values of the upper or lower cropping limit would affect the inferred extrapolated burning velocities.

Figure 8 shows the burning velocity of R-152a/air flames as a function of the lower cropping bound LB, with different curves for values of the upper cropping bound UB. Frames are presented for $\phi=0.9$, 1.1, and 1.4. Such plots for all of the refrigerant blends in the present paper are included in the supplementary materials. The red dot indicates the manually selected “optimum” value of the cropping limits OB, and the red error bars indicate a ± 5 % deviation on the burning velocity. The effect of the upper cropping bound generally gets larger as the lower cropping bound is increased. The upper cropping bound also has non-monotonic behavior. For example, in the rightmost frame of Figure 8 for $\phi=1.4$, raising the upper bound from 0.4 to 0.6 times the inflection point, lowers the extrapolated burning velocity; but then further raising from 0.6 to 0.8 to 1.0 raises it. This can be seen in Figure 3, for $\phi=1.4$, for which the burning velocity drops between 0.8 and 1.0 times the inflection point, which tends to force the curve fit flatter, making the extrapolated S_u larger. Figure 9 shows, for the reasonable range of $1.25 \leq LB \leq 2.5$ and $0.4 \leq UB \leq 1.0$, the maximum and minimum value of the extrapolated value of the burning velocity, normalized by the value at the manually determined optimum cropping limits. As indicated, at $\phi=1.1$, the maximum deviation resulting from that range of cropping limits is only about $\pm 8\%$; however, at $\phi=0.9$ it can be up to about 20% higher and for $\phi=1.4$, as much as 20 % lower than that obtained using OB.

Table 1. Manually selected (“optimum” bound, OB) for each mixture and fuel-air equivalence ratio.

Refrigerant	Ratio (v/v %)	Fuel-Air Equivalence Ratio						
		0.8	0.9	1.0	1.1	1.2	1.3	1.4
Lower Optimum Bound, P/P_0								
R-152a	100/0	1.8	1.6	1.8	2.0	2.0	2.0	1.7
R-152a/R-134a	80/20	1.5	2.0	2.0	1.7	1.8	1.6	1.6
	50/50	1.5	1.6	1.6	1.5	1.5	1.6	1.6
R-152a/R-1234yf	50/50	1.5	1.5	1.6	1.5	1.8	1.5	1.5
	40/60	N/A	1.7	1.8	1.6	1.6	1.6	1.5
Upper Optimum Bound, Fraction of $P_{\text{inflection point}}$								
R-152a	100/0	0.7	0.6	0.45	0.4	0.4	0.35	0.35
R-152a/R-134a	80/20	0.7	0.6	0.45	0.4	0.4	0.35	0.35
	50/50	0.75	0.75	0.75	0.75	0.55	0.5	0.45
R-152a/R-1234yf	50/50	0.7	0.65	0.65	0.6	0.45	0.35	0.3
	40/60	N/A	0.75	0.7	0.65	0.5	0.6	0.6

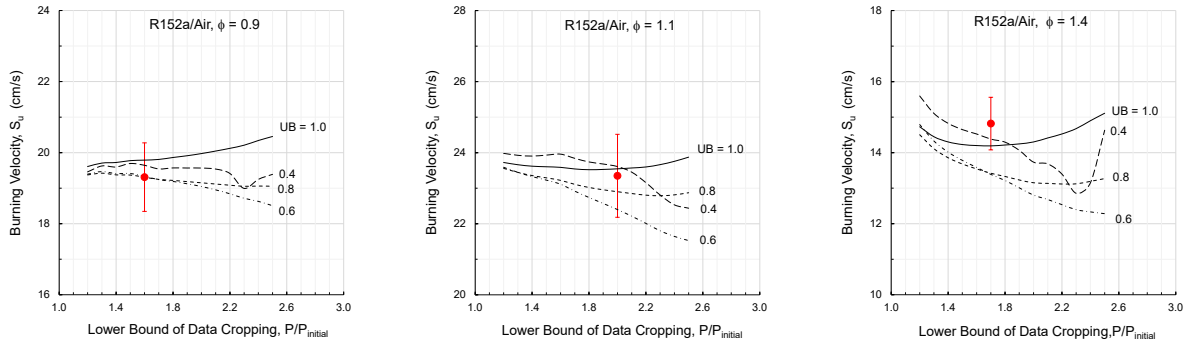


Figure 8 - Experimental burning velocity as a function of lower cropping limit for R-152a-air mixtures at $\phi = 0.9, 1.1,$ and 1.4 . Different curves are for different values of the upper cropping limit. The red dot indicates the manually selected “optimum” value, and the red error bars show a $\pm 5\%$ deviation on the burning velocity.

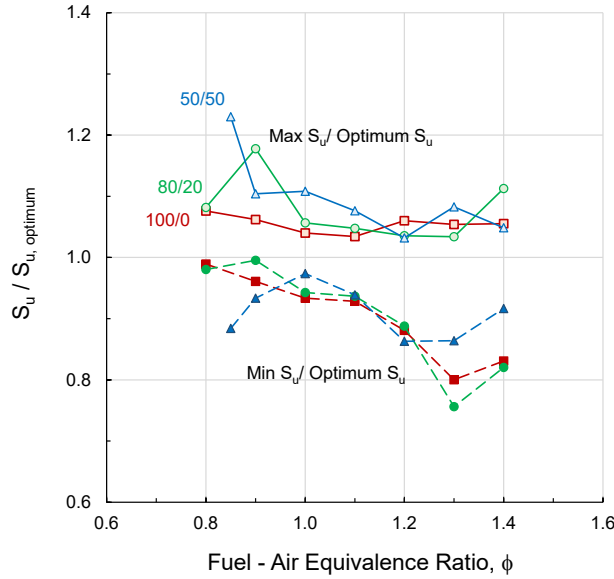


Figure 9 - Minimum and maximum S_u (over the range of cropping limits) divided by S_u from the manually determined optimum cropping limits, as a function of the fuel-air equivalence ratio. Different curves are shown for different ratios of R-152a and R-134a.

An important result, apparent from the curve of $\phi=1.4$ in Figure 3, is that limitations on UB due to transition to cellular behavior can sometimes leave little data if the lower cropping limit is too high. Based on the results for R32-air flames (Hegetschweiler et al., 2022, Hegetschweiler et al., 2023), however, it is expected that the stretch effects for the present flames of R152a/R134a/R1234yf will not be too important for richer flames (Law, 2010). Hence, the lower bound could be relaxed to obtain sufficient data for the curve fit and extrapolation without inaccuracies due to stretch effects at the smaller radii.

Note that the importance of data cropping for refrigerant flames has been discussed by other researchers. For example, Takizawa et. al (2013b) have discussed manually cropping the lower bound for ignition disturbances and using the inflection point as the upper bound. In later work (Takizawa et al., 2008), they have also discussed the importance of setting the upper bound to eliminate data affected by sudden acceleration of the flame. Similarly, Moghaddas et al. (2014) discuss flame wrinkling for R-152a flames and its consideration in the data reduction. Nonetheless, the effects of the lower and upper bounds on the extrapolated burning velocity at ambient conditions have not been systematically examined in previous work.

4.3 Reaction Path and Sensitivity Analyses

Although the kinetic mechanism is still at early stages of development and validation, the agreement shown in Figure 6 and Figure 7 is reasonable and hence it is useful to explore differences in the mechanism of decomposition of R-152a with added R-134a or R-1234yf via reaction path and sensitivity analyses. Figure 10 shows the reduction in the peak burning velocity (right scale) and the peak radical volume fraction in the flame zone (left scale) with added R-134a or R-1234yf. As indicated, a 50/50 molar blend of R-152a/R-134a is about equivalent to a 40/60 blend of R-152a/ R-1234yf, both reducing the burning velocity from about 25 cm/s for pure R-152a to about 10 cm/s with the additive. Note that for both additives, a volume fraction in the fuel of 50 % corresponds to a condition of unity volume fraction ratio for fluorine and hydrogen in the system (F/H=1). As indicated, OH and H steadily decreased as the additive increases,

while the fluorinated radicals CF_2 , CF_3 , and F increase up to the $\text{F}/\text{H}=1$ condition, then decrease after that, while O atom volume fraction increases up to $\text{F}/\text{H}=1$, and then increases more rapidly above that. Nonetheless, the sum of the hydrocarbon radical pool species (O , H , and OH) decrease as with additive addition. With the increase of concentration of the additive, the contribution of $\text{CF}_2\text{O}+\text{H}=\text{HF}+\text{CFO}$ and $\text{CF}_3+\text{H}=\text{CF}+\text{HF}$ increases, which competes with the chain-branching reaction $\text{H}+\text{O}_2=\text{OH}+\text{O}$. Also, the higher F/H ratio leads to lower H_2 volume fraction, decreasing the rate of the $\text{O}+\text{H}_2=\text{OH}+\text{H}$ branching reaction and reducing the consumption rate of O . This contributes to the increase in O atom, as do the reactions such as: $\text{CF}_3+\text{O}_2=\text{CF}_3\text{O}+\text{O}$ and $\text{CF}_3+\text{O}_2=\text{CF}_2\text{O}+\text{O}$, which become more important as the fluorinated radical volume fractions increase.

The flame reaction of R-152a has a large degree of hydrocarbon character with most of the decomposition reactions involving the hydrocarbon radicals H , O and OH . With additive addition to the fuel, the fraction of reactions proceeding through thermal decomposition reaction increases noticeably, for example from 50 % to 80 % of the consumption of R-152a, with addition of the two agents at 0 % or at their loading for $\text{F}/\text{H} \approx 1$.

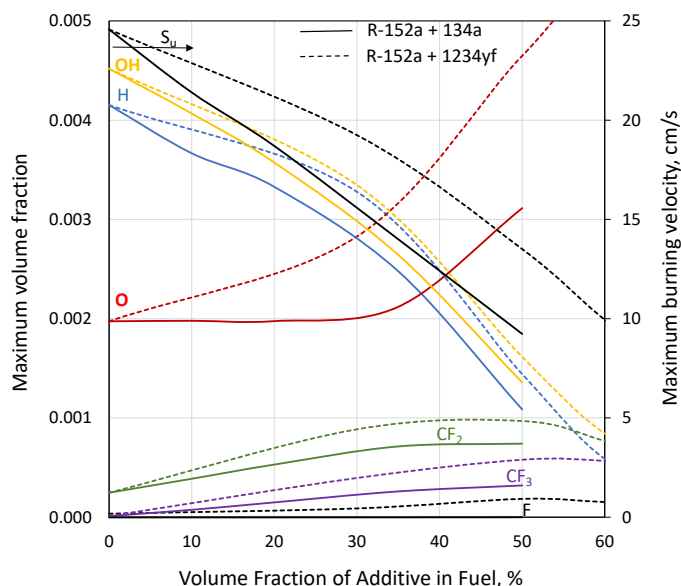


Figure 10- Maximum S_u over all ϕ (right scale) and peak radical volume fractions (left scale) as a function of added R-134a or R-1234yf in the fuel.

5. Conclusions

The laminar burning velocity of mixtures of R-152a with R-134a or R-1234yf added as a flame inhibitor has been determined using a constant volume method experiment. Data are presented for reactants at ambient initial conditions as well as for initial conditions at elevated temperature and pressure. For pure R-152a at ambient conditions, the present results are in good agreement with previous data in the literature for stoichiometric and rich conditions if a similar two-zone data reduction scheme neglecting radiation is employed. For lean conditions, the present results agree with prior experiments of the authors but are about 8% lower than another data source in the literature. With added R-134a, and again employing a two-zone data reduction model, the present burning velocities are significantly higher for rich flames and lower for lean flames than previously reported. Moreover, if radiation is included in the data reduction via an optically thin model for radiation, all the inferred burning velocities are higher, typically by about 5 % to

8 % higher for pure R-152a/air flames, 6 % to 15 % higher with added R-134a, and 9 % to 21 % with added R-1234yf (all at 298 K, 101 kPa initial conditions). Hence, properly specifying the actual radiation in the experiment is important for proper data reduction. The results are consistent for reactants at ambient conditions as well as at an elevated temperature pressure condition.

Since curve fits are required to extrapolate the burning velocity data back to the ambient condition and since the curve fits depend upon the upper and lower data cropping limits used, the effects of the cropping limits on the inferred burning velocity were explored. It is recommended to select the cropping limits based examination of the burning velocity versus pressure data so that the effects of ignition disturbance, wall effects and possible cellular flame formation can be eliminated. If other reasonable cropping limits are employed rather than the manually selected ones, the inferred burning velocity can be up to about 20% higher for lean flames and as much as 20% lower for rich flames.

Using a recently developed kinetic mechanism for the combustion of refrigerant/air flames, the steady, planar burning velocities were predicted using a 1-D flame code and compared to the experimental results. The agreement was generally good, properly capturing both the variation with ϕ and the variation with added less flammable component. Nonetheless the numerical predictions were sometimes closer to the experimental data obtained via the adiabatic assumption in the data reduction model, and sometimes closer to data obtained with the optically thin assumption. This is not of major concern, however, since the kinetic model was developed to provide a reasonable fit to the present data (as well as to other data).

Using the numerical results, reaction path and sensitivity analysis were used to understand changes in the R-152a decomposition path with addition of the highly fluorinated, less flammable refrigerants. Most of the flames had significant hydrocarbon character with radical reactions proceeding through the typical hydrocarbon chain branching radicals H, O, and OH. With addition of the more highly fluorinated compound, however, the degree of thermal decomposition reactions and fluorinated radical reactions increased significantly.

The largest uncertainties in the present work come from the consideration of radiation. Hence, in future work it would be useful to have a better understanding of thermal radiation from the flames. In the meantime, however, it is recommended to employ multi-zone data reduction models with and without radiation to bound the inferred burning velocity, and until better radiation parameters are available for the fluorinated products, select the average of the two results (OTM and ADI) for the burning velocity. Finally, for extrapolation to ambient conditions, the cropping limits do make a difference on the accuracy of the curve fit. It is recommended to manually select the cropping limits for each data set to eliminate the effect of ignition disturbances and stretch for small flames, and the effects of wall interactions and possible transition to cellular flames for larger flames. As with R32-air flames, it seems reasonable to select lower crop limits above $2P_0$ for lean flames, although further studies to understand the stretch effects of R152a/R134a/R1234yf blends in air for small flames in constant volume conditions would be useful, to see if they behave as did R32-air flames.

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Supplementary Materials

I Figures of additional data.

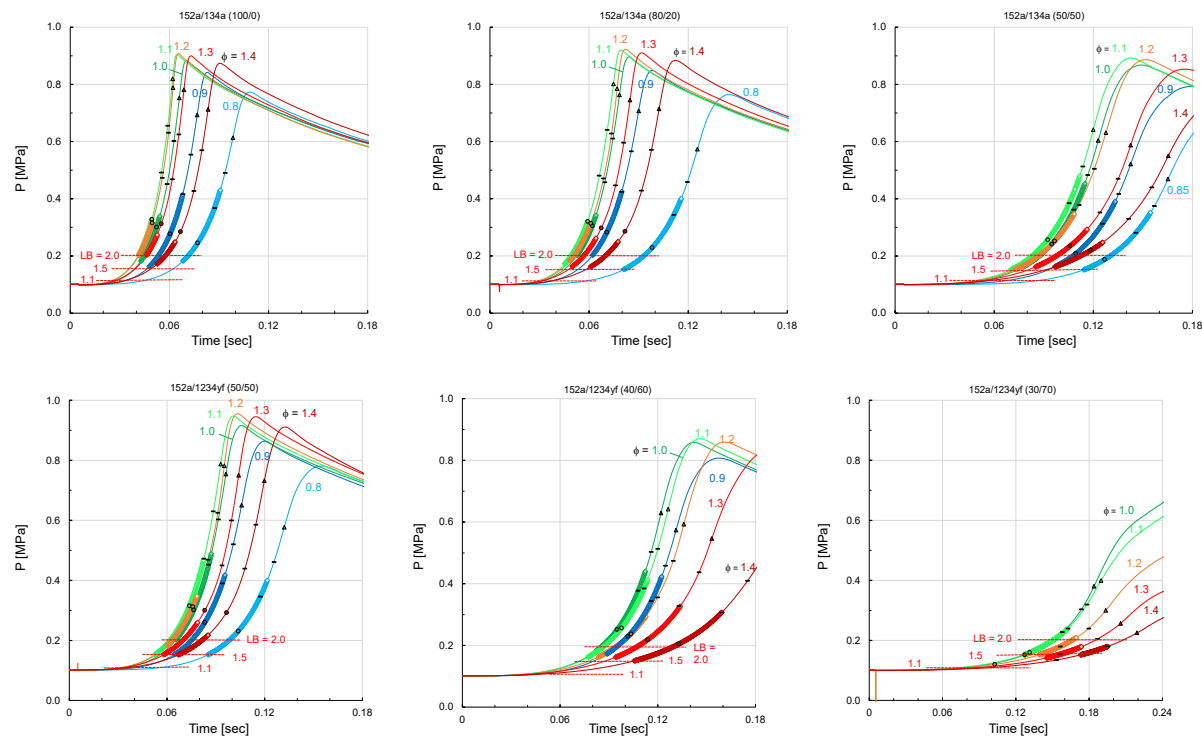


Figure S-1 - Experimental pressure rise history of R-152a/R-134a at molar ratios of 100/0, 80/20, and 50/50, and R-152a/R-1234yf at molar ratios of 50/50, 40/60, and 30/70. Data are presented for the indicated fuel-air equivalence ratio ϕ .

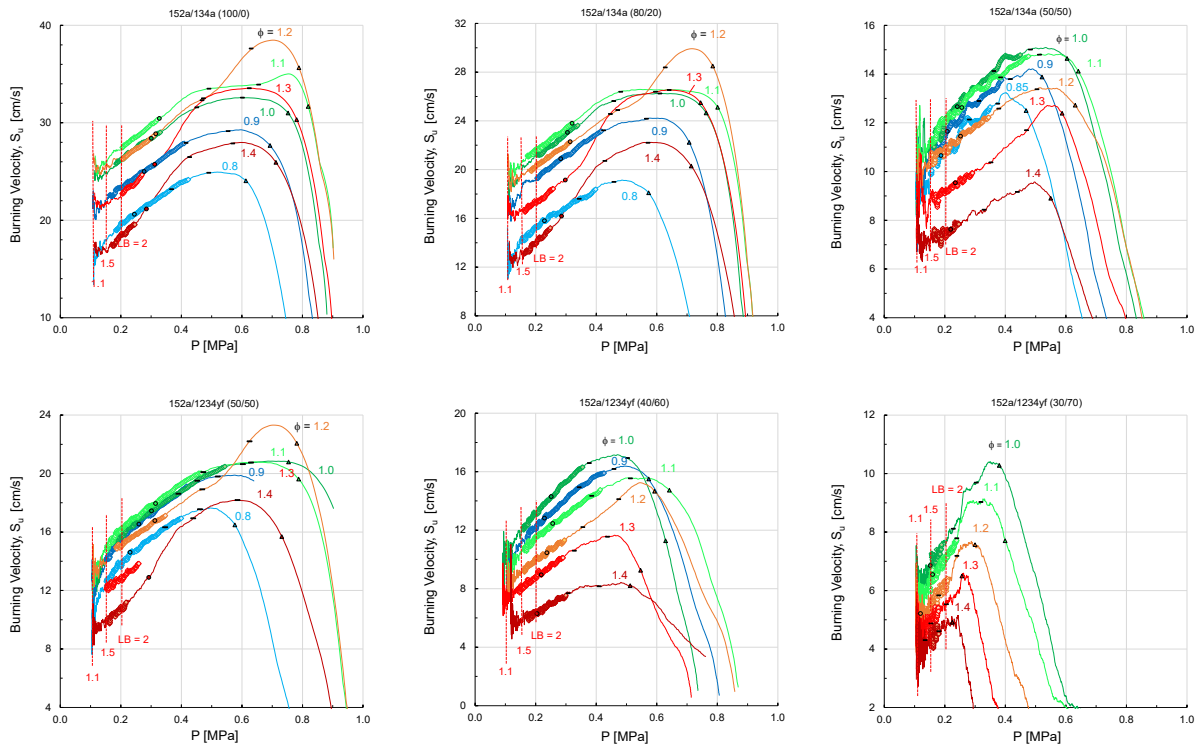


Figure S-2 Experimental burning velocities (S_u) as a function of unburned gas pressure for R-152a/R-134a at molar ratios of 100/0, 80/20, and 50/50, and R-152a/R-1234yf at molar ratios of 50/50, 40/60, and 30/70. Data are presented for the indicated fuel-air equivalence ratio ϕ .

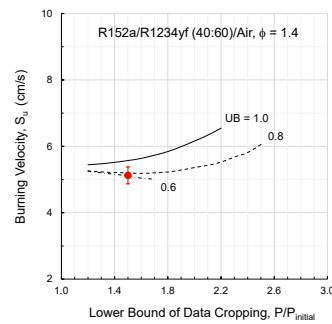
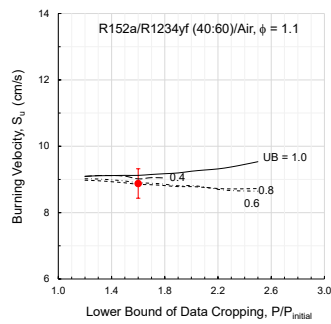
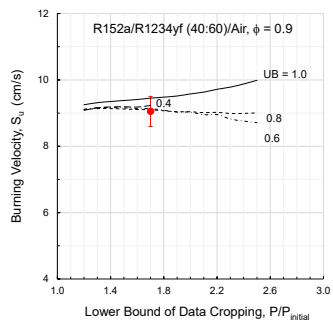
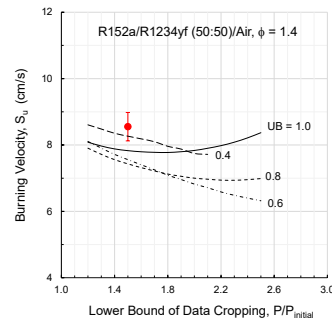
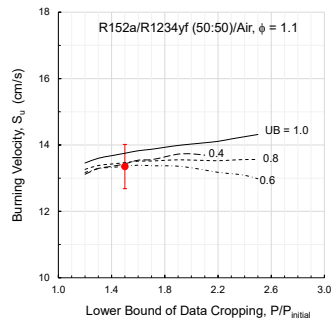
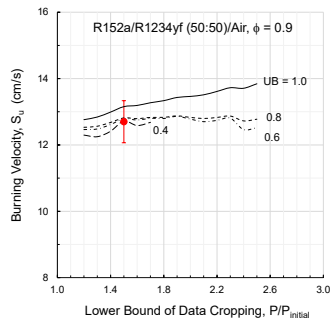
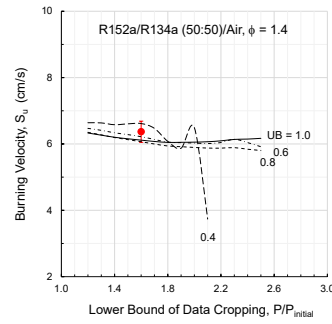
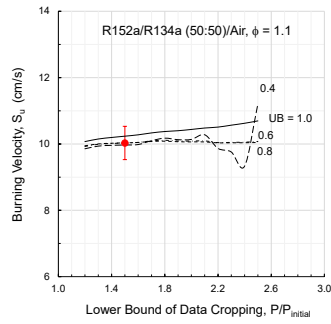
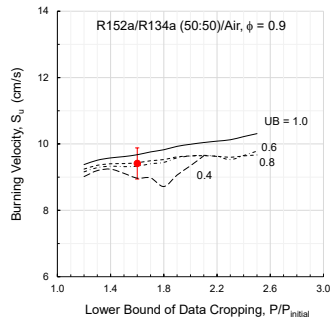
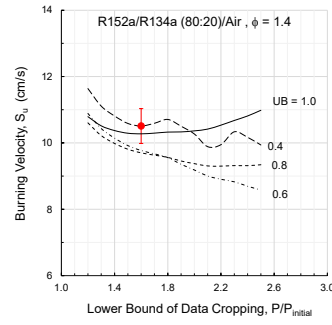
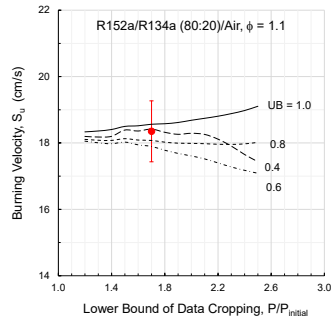
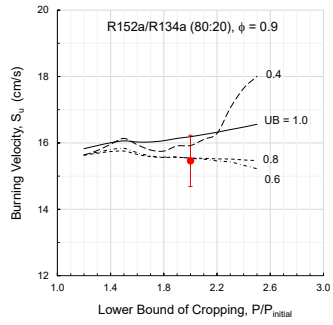
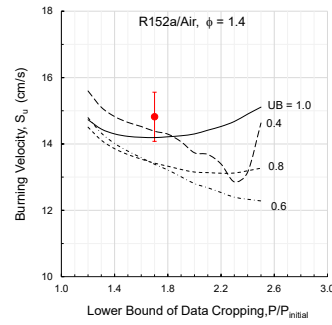
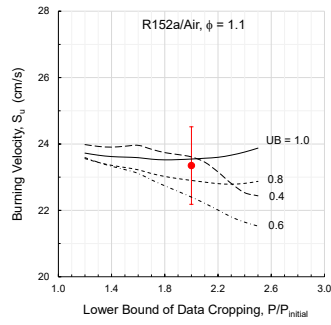
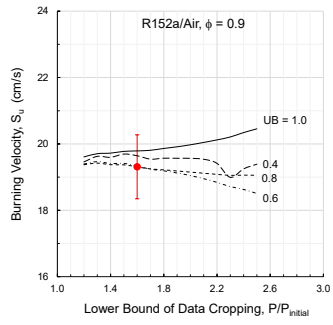


Figure S-3. Experimental burning velocity as a function of lower cropping limit for R-152a/R-134a at molar ratios of 100/0, 80/20, and 50/50, and R-152a/R-1234yf at molar ratios of 50/50, 40/60, and 30/70. Different curves are for different values of the upper cropping limit. The red dot indicates the manually selected “optimum” value, and the red error bars show a $\pm 5\%$ deviation on the burning velocity.

Supplementary Materials:

Tables of burning velocity data in figures.

Table A- 1: Burning velocity as a function of ϕ for R-152a/air mixtures. [19, 32], CVM, $X_{R-152a, \text{stoic}} = 0.0775$; initial conditions: $T_i = 298 \text{ K}$, $P_i = 0.101 \text{ MPa}$.

Takizawa et al. [19] two-zone		Burrell et al. [32] two-zone		Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]	ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.76	15.07	0.80	15.72	0.80	15.97	0.80	17.22
0.826	18.14	0.85	17.92	0.90	19.31	0.90	20.48
0.897	20.62	0.90	18.94	1.00	22.29	1.00	23.42
0.962	22.34	0.95	21.30	1.10	23.35	1.10	24.49
1.034	23.76	1.00	22.49	1.20	22.12	1.20	23.2
1.104	23.47	1.05	23.08	1.30	19.1	1.30	20.14
1.176	22.74	1.10	23.67	1.40	14.82	1.40	15.71
1.251	21.2	1.15	23.33				
1.317	17.48	1.20	22.32				
		1.30	19.78				

Table A- 2: Burning velocity as a function of ϕ for R-152a/air mixtures. CVM, $X_{R-152a, \text{stoic}} = 0.0775$; initial conditions: $T_i = 375 \text{ K}$, $P_i = 0.253 \text{ MPa}$.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.80	20.41	0.80	22.83
0.90	24.14	0.90	26.75
1.00	26.88	1.00	29.65
1.10	28.38	1.10	31.03
1.20	27.2	1.20	29.56
1.30	24.1	1.30	26.21
1.40	19.89	1.40	21.78

Table A- 3: Burning velocity as a function of ϕ for air with R-152a/R-134a mixtures at volume fractions of 80/20. [19], CVM, $X_{R-152a/R-134a \text{ at } 80/20, \text{stoic}} = 0.0837$; initial conditions: $T_i = 298 \text{ K}$, $P_i = 0.101 \text{ MPa}$.

Takizawa et al. [19] two-zone		Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
1.28	13.63	0.80	12.13	0.80	13.37
1.15	18.04	0.90	15.46	0.90	16.79
1.00	19.63	1.00	17.54	1.00	18.79
0.89	17.85	1.10	18.35	1.10	19.52

0.76	14.40	1.20	17.15	1.20	18.28
		1.30	14.59	1.30	15.55
		1.40	10.51	1.40	11.42

Table A- 4: Burning velocity as a function of ϕ for air with R-152a/R-134a mixtures at volume fractions of 80/20. CVM, $X_{R-152a/R-134a}$ at 80/20, stoic = 0.0837; initial conditions: $T_i = 375$ K, $P_i = 0.253$ MPa.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.80	15.54	0.80	17.96
0.90	19.73	0.90	22.35
1.00	21.64	1.00	24.36
1.10	22.41	1.10	25.02
1.20	21.03	1.20	23.40
1.30	18.22	1.30	20.35
1.40	15.27	1.40	17.19

Table A- 5: Burning velocity as a function of ϕ for air with R-152a/R-134a mixtures at volume fractions of 50/50. [19], CVM, $X_{R-152a/R-134a}$ at 50/50, stoic = 0.0950; initial conditions: $T_i = 298$ K, $P_i = 0.101$ MPa.

Takizawa et al. [19] two-zone		Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.77	9.60	0.85	8.66	0.85	9.93
0.83	11.04	0.90	9.41	0.90	10.76
0.94	11.71	1.00	9.91	1.00	11.22
1.00	11.71	1.10	10.03	1.10	11.34
1.12	10.56	1.20	9.29	1.20	10.43
1.24	8.25	1.30	7.83	1.30	8.88
		1.40	6.37	1.40	7.28

Table A- 6: Burning velocity as a function of ϕ for air with R-152a/R-134a mixtures at volume fractions of 50/50. CVM, $X_{R-152a/R-134a}$ at 50/50, stoic = 0.0950; initial conditions: $T_i = 375$ K, $P_i = 0.253$ MPa.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.85	11.48	0.85	13.98
0.90	12.31	0.90	14.86
1.00	12.99	1.00	15.53
1.10	12.85	1.10	15.36
1.20	11.66	1.20	13.98
1.30	9.97	1.30	12.09
1.40	7.95	1.40	9.87

Table A- 7: Burning velocity as a function of ϕ for air with R-152a/R-1234yf mixtures at volume fractions of 50/50. CVM, $X_{R-152a/R-1234yf}$ at 50/50, stoic = 0.0775; initial conditions: $T_i = 298$ K, $P_i = 0.101$ MPa.

Present Study Present Study

two-zone		multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.80	11.11	0.80	12.41
0.90	12.70	0.90	13.99
1.00	13.39	1.00	14.65
1.10	13.35	1.10	14.62
1.20	12.60	1.20	13.84
1.30	10.79	1.30	11.79
1.40	8.55	1.40	9.45

Table A- 8: Burning velocity as a function of ϕ for air with R-152a/R-1234yf mixtures at volume fractions of 50/50. CVM, $X_{R-152a/R-134a}$ at 50/50, stoic = 0.0775; initial conditions: $T_i = 375$ K, $P_i = 0.253$ MPa.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.80	14.91	0.80	17.43
0.90	16.88	0.90	19.51
1.00	17.53	1.00	20.21
1.10	17.38	1.10	20.01
1.20	16.09	1.20	18.55
1.30	13.81	1.30	16.03
1.40	11.78	1.40	13.81

Table A- 9: Burning velocity as a function of ϕ for air with R-152a/R-1234yf mixtures at volume fractions of 40/60 in dry condition. CVM, $X_{R-152a/R-1234yf}$ at 40/60, stoic = 0.0775; initial conditions: $T_i = 298$ K, $P_i = 0.101$ MPa.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.90	9.05	0.90	10.39
1.00	9.45	1.00	10.70
1.10	8.88	1.10	9.95
1.20	7.85	1.20	8.81
1.30	6.30	1.30	7.23
1.40	5.13	1.40	5.92

Table A- 10: Burning velocity as a function of ϕ for air with R-152a/R-1234yf mixtures at volume fractions of 40/60 in dry condition. CVM, $X_{R-152a/R-134a}$ at 40/60, stoic = 0.0775; initial conditions: $T_i = 375$ K, $P_i = 0.253$ MPa.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
0.90	13.12	0.90	15.64
1.00	13.50	1.00	15.93
1.10	12.51	1.10	14.67

1.20	10.91	1.20	12.91
1.30	9.28	1.30	11.13
1.40	7.37	1.40	9.09

Table A- 11: Burning velocity as a function of ϕ for air with R-152a/R-1234yf mixtures at volume fractions of 30/70 in dry condition. CVM, $X_{\text{R-152a/R-1234yf}}$ at 30/70, stoic = 0.0775; initial conditions: $T_i = 298$ K, $P_i = 0.101$ MPa.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
1.00	5.76	1.00	6.41
1.10	5.38	1.10	6.15
1.20	4.62	1.20	5.38
1.30	3.83	1.30	4.62
1.40	3.58	1.40	4.21

Table A- 12: Burning velocity as a function of ϕ for air with R-152a/R-1234yf mixtures at volume fractions of 30/70 in dry condition. CVM, $X_{\text{R-152a/R-134a}}$ at 30/70, stoic = 0.0775; initial conditions: $T_i = 375$ K, $P_i = 0.253$ MPa.

Present Study two-zone		Present Study multi-zone (OTM)	
ϕ	S_u [cm/s]	ϕ	S_u [cm/s]
1.00	8.93	1.00	11.19
1.10	8.15	1.10	10.21
1.20	7.18	1.20	9.13
1.30	6.87	1.30	8.95
1.40	5.65	1.40	7.44