ENCIT-2018-0593
PROPAGATION OF ANHYDROUS ETHANOL-AIR FLAMES WITH DISTINCT EQUIVALENCE RATIOS AT SUB-ATMOSPHERIC PRESSURE

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Abstract. The main parameter to characterize mixtures combustion is the laminar flame velocity. This project aims to gather data concerning the premixed laminar flame velocities of anhydrous ethanol-air mixtures under a predetermined pressure of 60 kPa for different equivalence ratios, at room temperature, in order to ascertain the influence of this factor in the premixed laminar flame velocity itself. The mixture is contained in a transparent propagation tube after homogeneity is achieved in a preliminary mixture preparation chamber. A spark in one of the ends ignites it, giving rise to the flame, and its propagation is recorded using a high speed camera. Finally, the flame velocity throughout the extension of the tube is measured by video analysis. Results demonstrated that the equivalence ratio has a considerable influence over the flame speed, leading to significant variations in its magnitude.

Keywords: Combustion, premixed laminar flame velocity, ethanol.

1. INTRODUCTION

In the field of study of premixed flames, the following questions should be considered (McAllister, et al., 2011): how fast will the flame consume the unburned mixture? How is the propagation affected by varying conditions, such as pressure, temperature and equivalence ratio?

The present work innovates by determining the laminar flame velocities of anhydrous ethanol-air mixtures with distinct compositions under a sub-atmospheric pressure of 60 kPa. Therefore, it is of vital importance to combustion science.

A flame is the propagation of a local and self-sustaining combustion zone in subsonic velocities (Turns, 2000). Figure 1 represents the propagation of a flame from the combustion of an ethanol-air mixture in one of the experimental tests performed.

It is noted that the flame itself occupies a small portion of the combustible mixture, consuming the reactants as it propagates inside the tube. According to Carvalho (2007), the laminar flame velocity can be defined as the velocity with which the reactants, or unburned gases, enter the flame, considering the system of reference fixed to the flame.

The flame observed in this project is a tulip flame. This particular shape is often detected during the laminar flame propagation in long, closed or half-open (closed at ignition end) combustion chambers (Ponizy et al., 2014). It has been the object of study of several researches: Dunn-Rankin and Sawyer (1998) have discussed this phenomenon in closed tubes; Kratzel et al. (1998) has studied the transition between a turbulent, high speed flame to a tulip flame; Xiao et al. (2014) studied the influence of ignition location in closed finite tubes on tulip flames; Hariharan and Wichman (2013) elaborated a new explanation on the formation of tulip flames, studying propagation in a rectangular channel.

The four essential phases of a tulip flame are described as follows: (a) the spherical flame occurs near the ignition point, as the flame initially propagates radially; (b) the long flame, or also known as finger flame, has a greater area than other flame stages, hence its greater velocity; (c) the tulip flame is associated with the inversion of the flame front; (d) oscillatory propagation of the tulip flame until the end of the chamber.
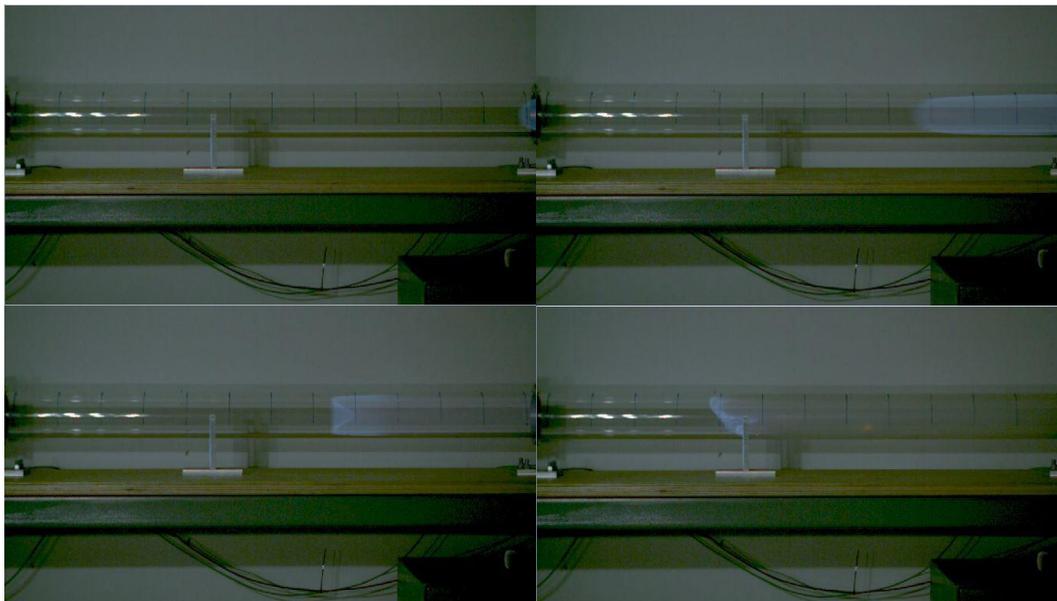
Figure 1. Premixed laminar flame of an anhydrous ethanol-air mixture at 60.2 kPa, 33.0 °C and equivalence ratio equal to 1.00.

The study of premixed flames has numerous industrial applications. For instance, when a fast combustion and low flame lengths are required, the use of a premixed fuel is desirable. The premixed laminar flame velocity is an important parameter to stabilize a flame, determine heat transfer rates and combustion efficiency in gas turbines via the relationship between the laminar and turbulent flame velocities (Lefebvre and Ballal, 2010).

Ethanol is a biofuel whose utilization in the aeronautic industry is being considered. The majority of the studies regarding ethanol aim at internal combustion engines operation, thus, laminar flame velocity data is restricted to atmospheric pressures or greater. Jet a and Jet A-1 fuels are predominant in commercial aviation. Due to its cost and availability, Jet A is the most used fuel in the United States of America, while Jet A-1 is the most used worldwide (CHEVRON, 2007). In 1984, Jet fuel consumption was over 1840 thousand barrels per day. In 2010, this number increased to 5201 thousand barrels per day (INDEX MUNDI, 2016). Hence, alternative fuels should be considered for aviation. The International Air Transport Association (IATA) focuses on the reduction of greenhouse effect gases emissions in commercial aviation. IATA publishes annual reports on alternative fuels, and, although ethanol is mentioned in two recent reports (IATA, 2015; IATA, 2014), further studies are still necessary.

2. METHODOLOGY

The experimental tests were conducted in the facilities of the Instituto Nacional de Pesquisas Espaciais (INPE), located in Cachoeira Paulista, SP, in view of the viability and safety of the project. Figure 2 shows a schematic of the apparatus used in the project. The apparatus mainly consisted of a flame propagation tube, a mixture preparation chamber, a high speed video camera and a data acquisition system.

The mixing chamber was composed of a stainless-steel chamber housing a borosilicate spherical vessel of 20 L. The chamber also had electrical resistances in its interior to provide heating to the mixture and a pressure transducer capable of measuring pressures up to 200 kPa. There was a Type-K thermocouple inside the vessel to monitor the mixture temperature and another thermocouple inside the chamber (outside the vessel) to control the chamber temperature. The ethanol-air mixtures were prepared by the partial pressures method.

First and foremost, a vacuum pump evacuated the spherical vessel to a pressure of 0.5 kPa or lower. Then, ethanol was introduced into the mixture chamber up to the desired partial pressure. The heating system would ensure the ethanol did not condensate inside the chamber. After, air was introduced up to the final desired pressure. Subsequently, the mixture was left to rest for approximately 25 minutes while the magnetic stirrer ensured mixture homogeneity. Finally, after the mixture was ready, it was exhausted from the chamber, entering the propagation tube progressively, until the pressure inside the tube reached 60 kPa.

The propagation tube, as the spherical vessel, was made of borosilicate, having a diameter of 9.70 cm and a length of 150 cm, and was mounted on a table using aluminum holders in each end. The electrodes, located in one extremity of the tube, would generate a spark, which caused the ignition of the combustible mixture inside the tube. Hence, the flame would go from one end to another, and its movement was recorded by the high speed video camera. The camera used in this experiment was the FASTEC TS3, which is able to record at 1000 fps. The holders allocated two pressure transducers of 200 and 1000 kPa absolute pressure, a fast response thermocouple and a overpressure valve fixed at

500 kPa. The first pressure transducer was responsible of measuring the pressure during the filling process, while the second measured pressure during the combustion of the mixture.

The spark was produced by a transformer connected to one of the electrodes, which provided a voltage of 15 kV and an electric current of 30 mA. The other electrode was connected to a ground wire. The open source software Tracker was used to obtain the flame speeds from each video.

Hereafter, the cleaning process is discussed. Initially, for the tube, the combustion gases were forced out via a nitrogen stream. After that, it was filled two times with nitrogen, a third time with air, and it was evacuated each time by the vacuum pump. The same applies for the mixing chamber: it was filled two times with nitrogen, then finally with air, and, like the tube, it was evacuated each time. Using air as the last step for cleaning the mixing chamber guaranteed that, if any gas remained after the vacuum procedure, it would be air. Its presence was considered by measuring its pressure, so the overall mixture was not affected.
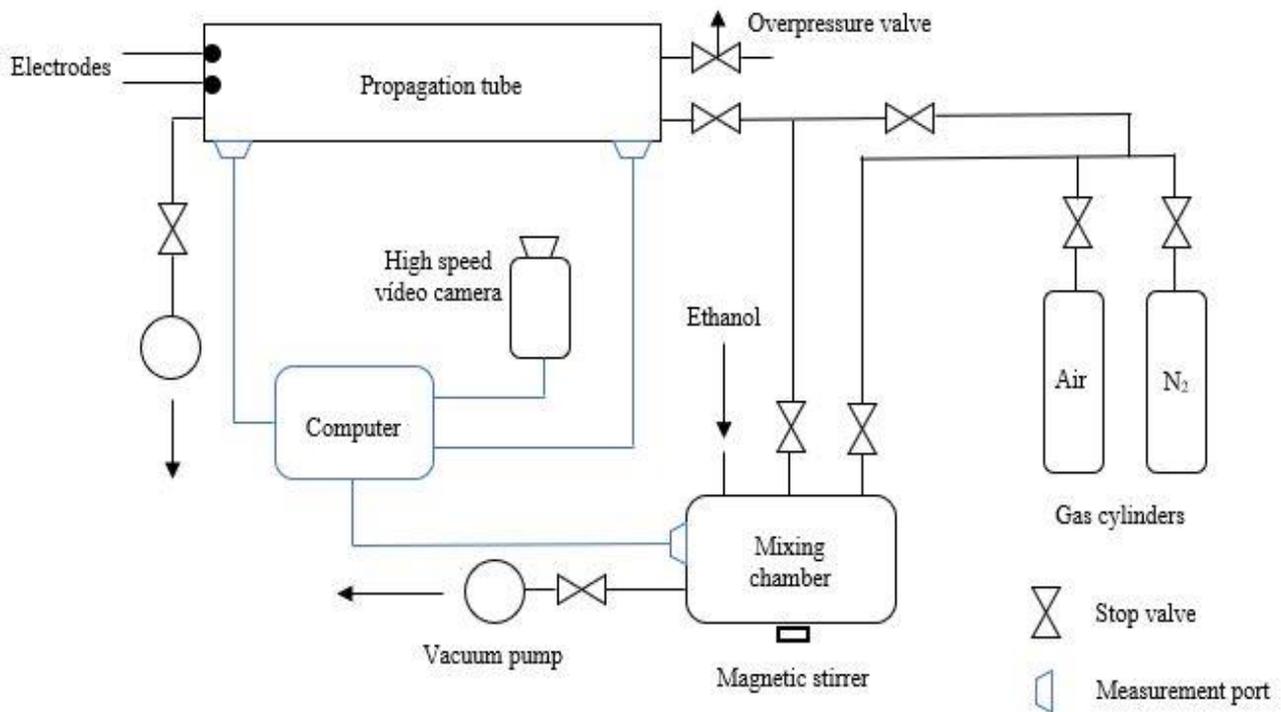

Figure 2. Schematic of experimental apparatus.

## 3. RESULTS AND DISCUSSION

The results presented in this section concern flame speeds at the first and second half of the propagation tube separately (Figure 3 and 4, respectively), for mixtures at 60 kPa and whose equivalence ratios (Φ) vary from 0.80 to 1.40. It is important to note that each condition was tested three times, however, these plots encompass the results of one of theses repetitions. The same behavior was observed in the tests not included in the graphics. The reference frame was fixed to the laboratory.

In Fig. 3, it is evidenced global maximum flame speeds are of order of 3500 cm/s and they were achieved for Φ around 1.00 and 1.10. On the other hand, the mixture with $\Phi = 0.80$ had a maximum speed of approximately 1800 cm/s. As mixtures got richer, their maximum speed decreased, from 3100 cm/s ($\Phi = 1.20$) to roughly 2000 cm/s ($\Phi = 1.40$). It is noted that slower flames experienced a deceleration sooner than their counterparts.

Figure 4 shows flame speeds determined after the flame has traveled the first 60 cm of the propagation tube. It is seen that the flame speeds present great variability, along with a continuously decrease in their magnitude. However, the decrease is not uniform since the flame was undergoing changes in its shape and area. Flame speeds at the end of the tube are between 200 and 130 cm/s for the different equivalence ratios.
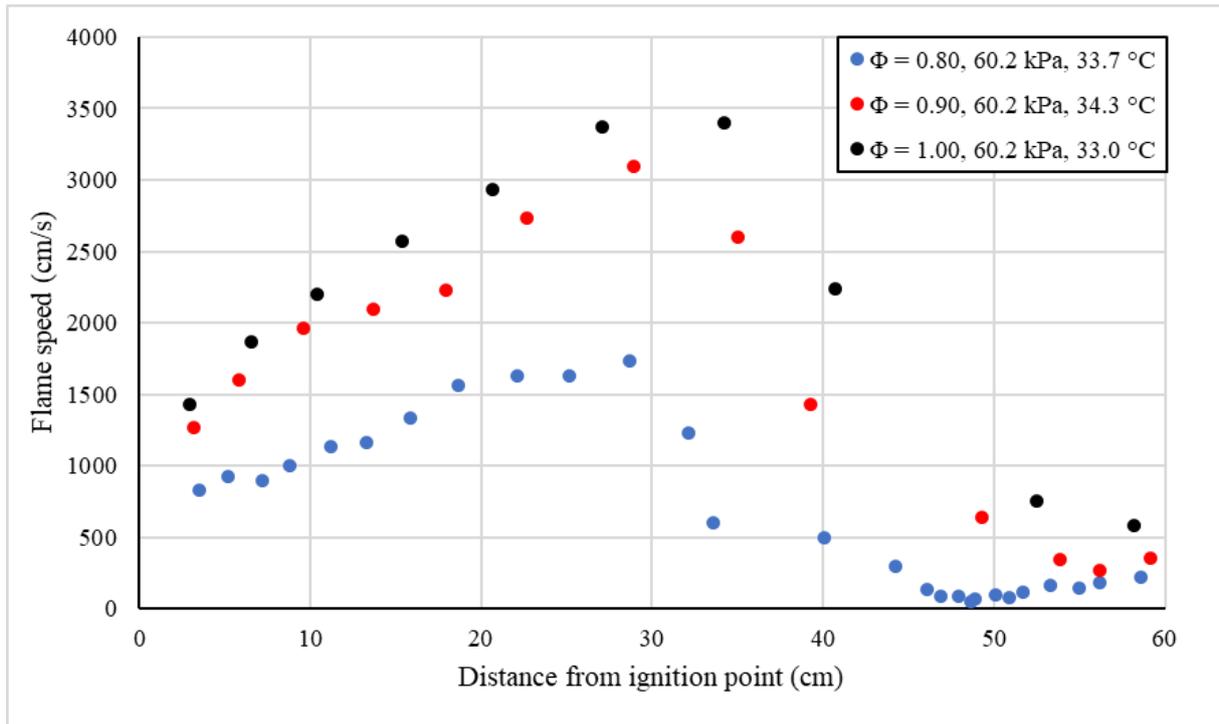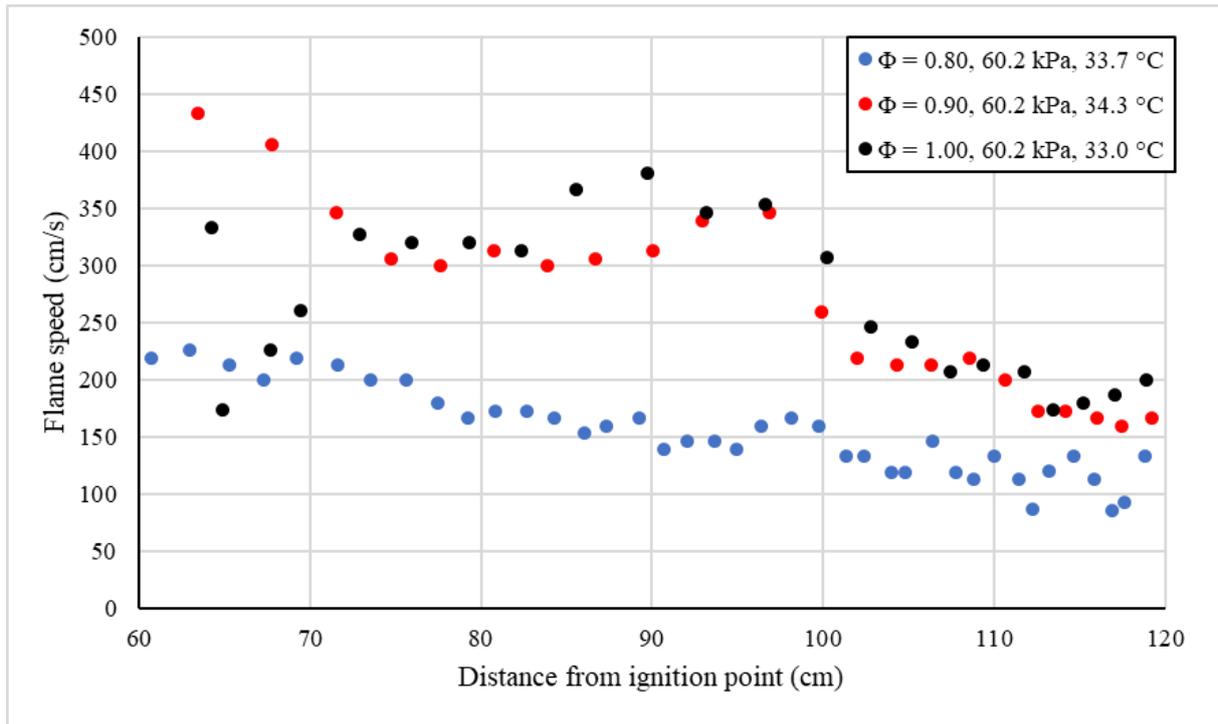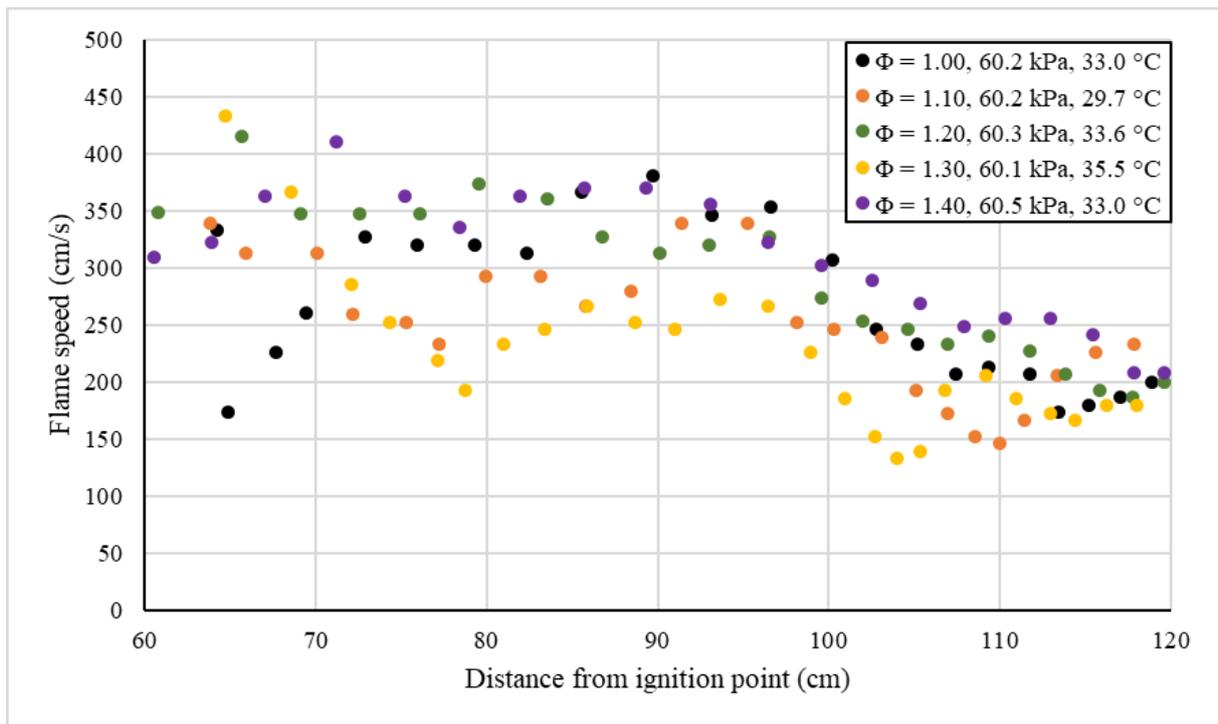
(a) Lean and stoichiometric mixtures.
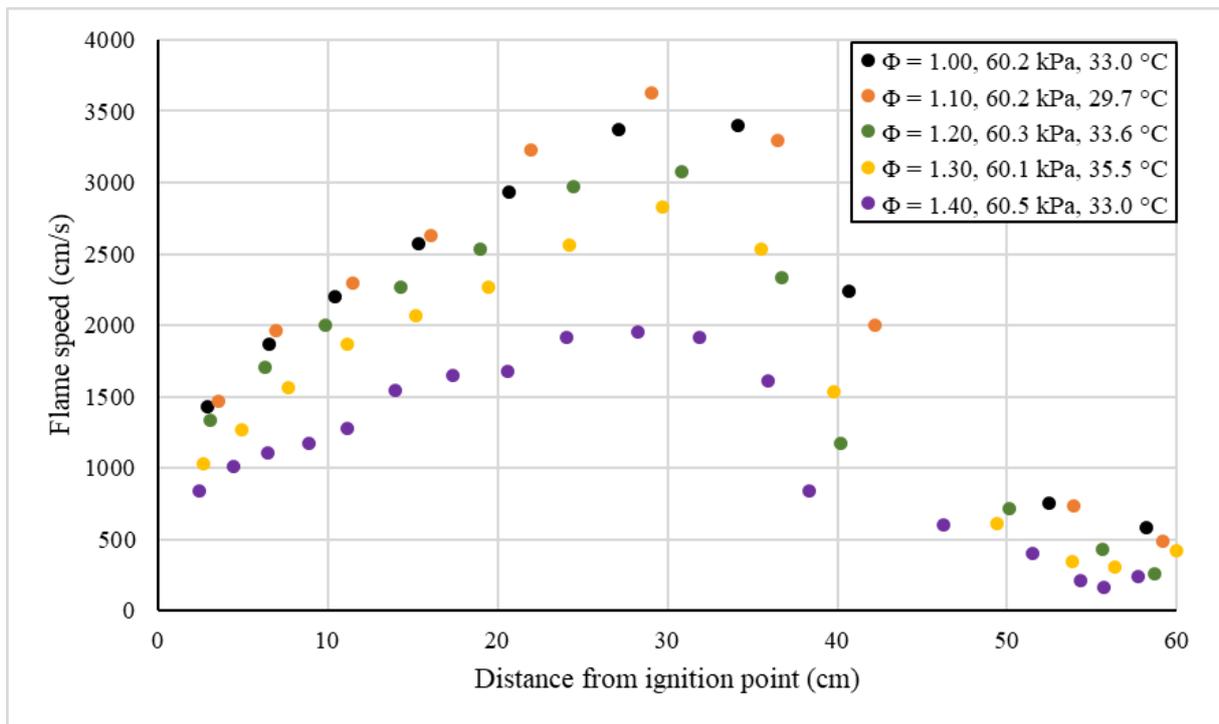
(b) Rich and stoichiometric mixtures.

Figure 3. Flame across the first half of the tube for ethanol-air mixtures with different equivalence ratios at 60 kPa.

(a) Lean and stoichiometric mixtures.


(b) Rich and stoichiometric mixtures.

Figure 4. Flame across the second half of the tube for ethanol-air mixtures with different equivalence ratios at 60 kPa.

Konnov et al. (2011) measured the laminar burning velocity of ethanol-air mixtures for different values of Φ and temperatures, while the pressure was left constant at 100 kPa. At 298 K, the laminar burning velocities were 40.1 cm/s for a Φ value of 1.00 and 42.5 cm/s for Φ equal to 1.10. In the present work, the maximum value of the flame speeds measured is about 80 times the laminar burning velocity estimated by Konnov et al. In the end of the tube, the flame speeds fall to 3 to 5 times that value.
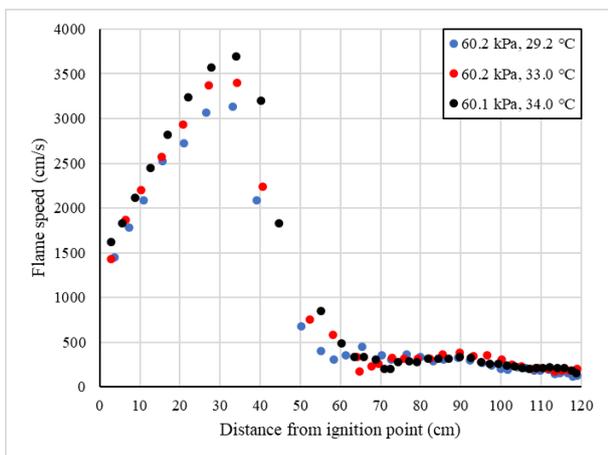
The complete histories of the flame speeds along the entire extension of the tube are shown in Fig. 5, for each mixture composition. The three tests for each condition are shown.
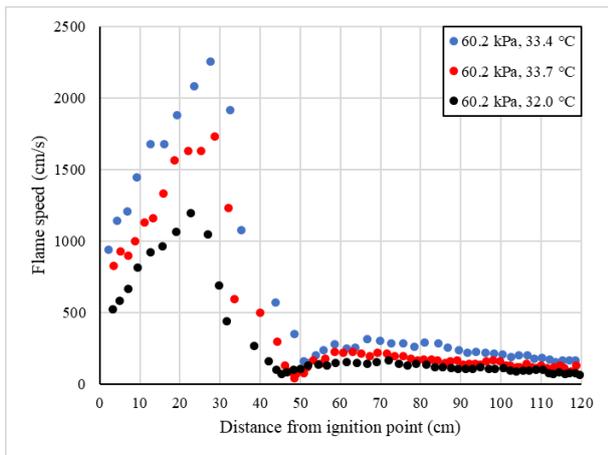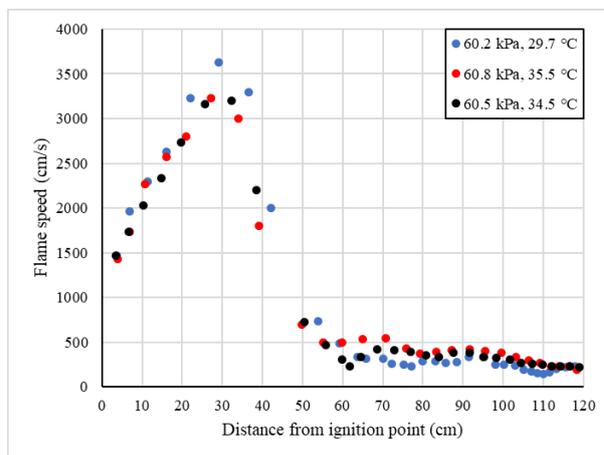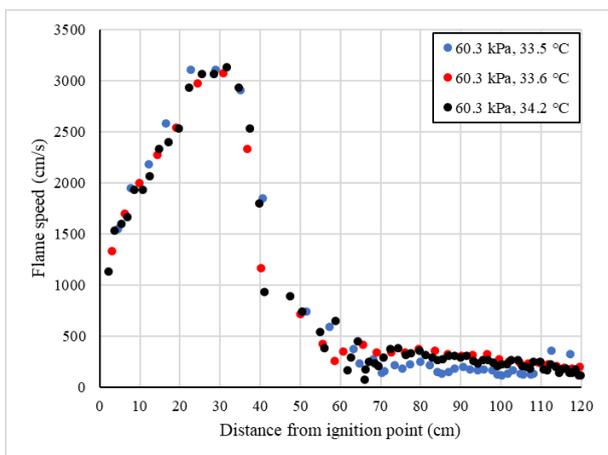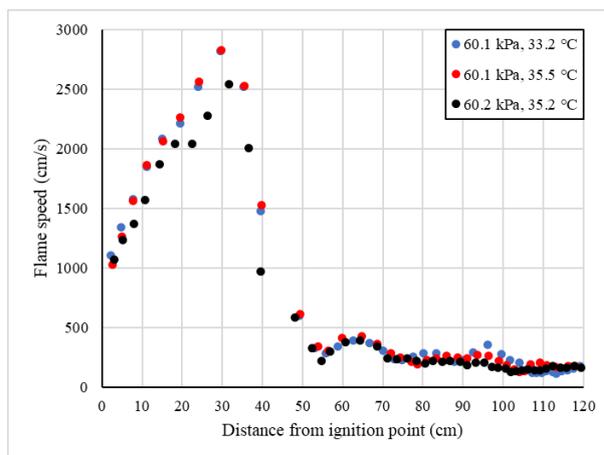

(a) $\Phi = 0.80$.
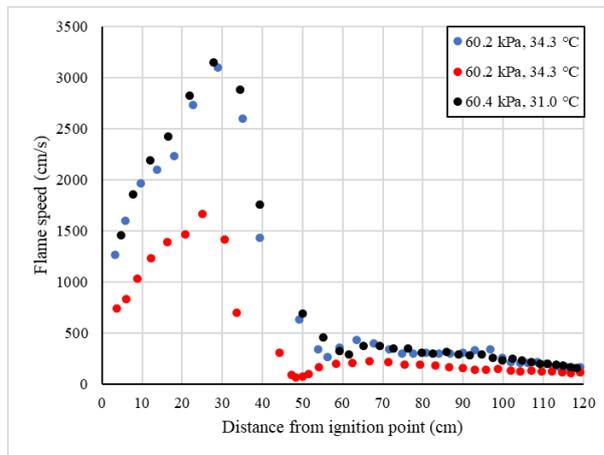
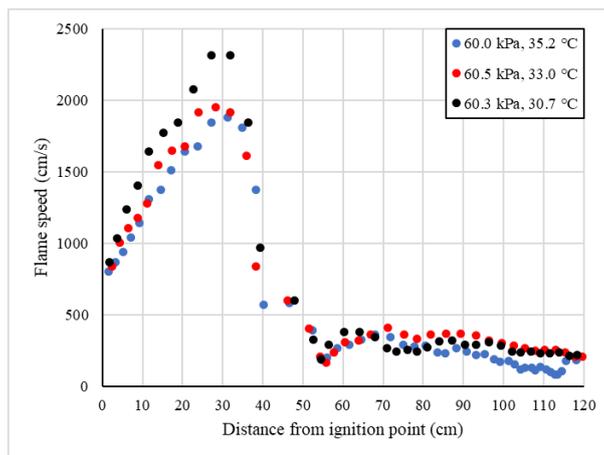(b) $\Phi = 0.90$.

(c) $\Phi = 1.00$.

(d) $\Phi = 1.10$.

(e) $\Phi = 1.20$.

(f) $\Phi = 1.30$.

(e) Φ = 1.40.

Figure 5. Ethanol-air flame speeds along a closed propagation tube for mixtures at 60 kPa.

Figure 5 illustrates that all flames in the present work suffered a rapid acceleration near the ignition point up to a peak value, followed by a also rapid decrease in their speed. As stated by Ponizy et al. (2014), this deceleration is associated to the formation of the tulip flame. A zone of high speed instability occurs after the decrease in velocity, and finally the flames assume an oscillatory propagation until the end of the tube, while presenting a continuously deceleration.

4. CONCLUSION

Results gathered in the present project have demonstrated the effect of the equivalence ratio of a premixed mixture on its flame speed when propagating inside a closed tube with ignition happening on one of its ends. As discussed, this parameter is essential to have a better control on the flame propagation, as small variations in the composition of the ethanol-air mixture can lead to significant alterations to the flame speed.

Further tests regarding different pressures and temperatures become necessary to develop a full understanding on premixed laminar flame velocities of ethanol-air mixtures.

5. ACKNOWLEDGEMENTS

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