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### EXPERIMENTAL INVESTIGATION OF LIQUID FUEL EVAPORATION

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**Abstract.** *In this article, liquid fuel is mixed with a pre-heated air to be fully evaporated. Parameters as equivalence ratio and inlet temperature were verified. Ethanol was used to preliminary results. Different equivalence ratios were tested with different inlet temperatures to verify its evaporation, increasing the air heater power to get full evaporation. It was possible to verify visually and graphically the evaporation of the fuel. Also, the capacity of the system to supply heat to air and fuel flow was verified, in order to future tests with another liquid fuels.*

**Keywords:** *liquid fuel, evaporation, ethanol*

#### 1. INTRODUCTION

Many researchers have been studying different liquid fuels evaporation characteristics to aim the energy efficiency increase in combustion processes and decrease of the pollutant emissions. Some of the fuel used nowadays is actually a mixture of different types of fuels. This procedure can reduce emissions and improve performance of combustion systems (Faik and Zhang, 2018).

The study of fuel's evaporation aspects and the mixing of fuel and air are important for designing combustors. Fuel evaporation characteristics can determine the local equivalence ratio in the combustor and affect combustion efficiency, which affects the temperature distribution and combustion products at the combustor outlet (Yan, et al., 2016).

In order to properly mix the air and fuel, "liquid fuel requires to be broken up into small droplets [...]" (CHIGIER, 1976). This result can be achieved using fuel atomizers, resulting in a fuel spray. Onuma and Ogasawara (1975) explored the sub-divisions of the spray flame, showing that its inner part is a result of a two-phase mixture droplet evaporation. Besides, Chigier (1976) also affirm that the study of a single droplet "[...] is directly relevant to the burning of liquid fuel sprays."

Due to the importance of this study field, fuel evaporation characteristics are being evaluated through the study of single droplet evaporation. Yang, et al. (2015) performed an experimental investigation of the evaporation characteristics of ethanol-diesel blend fuel using the droplet suspension technique. This study analyzed the droplet temperature and behavior along its life-time.

Faik and Zhang also studied the multi-component fuel droplet by using the high-speed camera technology and suspended droplet technique. In this study, single biodiesel/diesel and ethanol/diesel droplets were burned, and it was possible to verify phenomena such as bubble formation, internal circulation, puffing and micro-explosion. Also, it was possible to check the probability of sub-droplet formation and its affect in the droplet lifetime.

Therefore, the study of fuel droplets and its evaporation characteristics represents an important study field. On the other hand, these studies do not take in account the relation between the droplet and other physical boundaries, as well as with other droplets. Thus, the present study was conducted to check the evaporation characteristics of ethanol droplet inside a hot fuel pipe, with different equivalence ratio and fuel flow.

#### 2. METHODOLOGY

The experimental setup was mounted in order to analyze the evaporation of ethanol. Fuel evaporation will be tested for different equivalent ratios ( $\Phi$ ) and initial air temperature ( $T_{in}$ ).

The whole system was composed by the components listed in Table 1. The components were arranged as shown in Figure 1.

The air was heated by a resistance wrapped in a 3/4-inch steel tube, which can provide a power of up to 750W. Its control is given through a potentiometer, being able to regulate the peak of alternated voltage in up to 310V.

To supply ethanol to the air stream, a tank made of PVC with a 100 mm tube, sealed with weldable covers at its ends, with a total capacity of 3 Liters was used. At the upper end, there is a compressed air line, which provides pressure to tank. After leaving the tank, ethanol goes thru a little peristaltic pump controlled by a stepper motor, providing good control for small flows. The tank is located on top of a 0.01g resolution UX4200 SHIMADZU electronic mass scale, which has a fast response and is used for the calculation of fuel flow. In the end of the fuel line, there is an injection nozzle, which has a 1mm diameter and is connected directly in the airflow provided by the heater.

The air flow control was done manually by a flow control valve, with optimum precision and adjustment. For the measurement of air flow, a flowmeter with a resolution of 0.1 liters per minute of air was used. During all the tests, this system was stable and did not vary the flow supplied to the heater.

Name	Brand
Air Compressor	Schulz
Flow Meter 0-	Alicat
Data Acquisitor	Novus
Eletronic mass scale	Shimadzu
Air Heater	-
Ethanol Tank	-
Peristaltic Pump	-
Thermocouples "T"	-

Table 1. System components

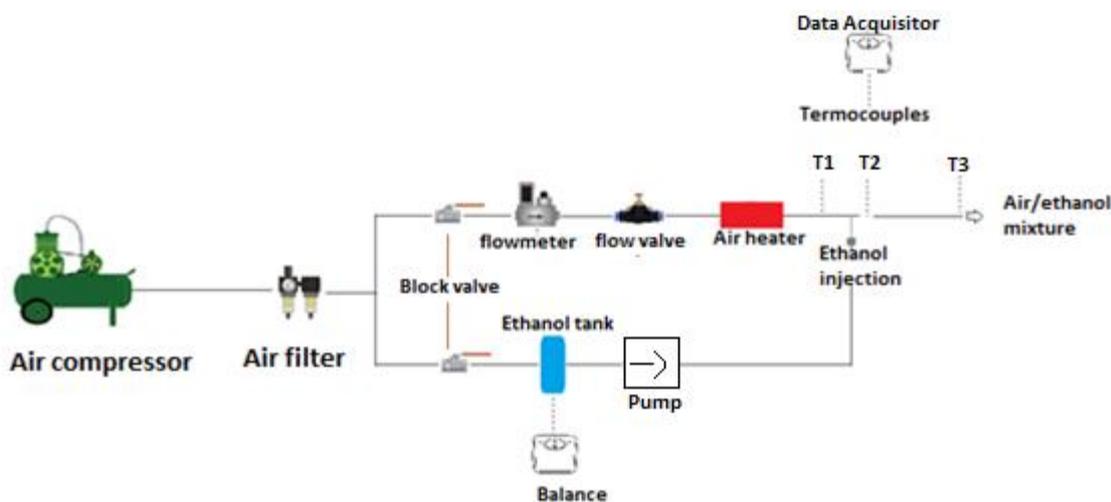


Figure 1. Arrangement of the system

The test section is composed by Teflon lines, which can support temperatures up to 250 °C. There are three thermocouples positioned thru the test section, one before the ethanol nozzle, one after the ethanol nozzle and one in the end of the Teflon line. The test section setup is showed in figure 2.

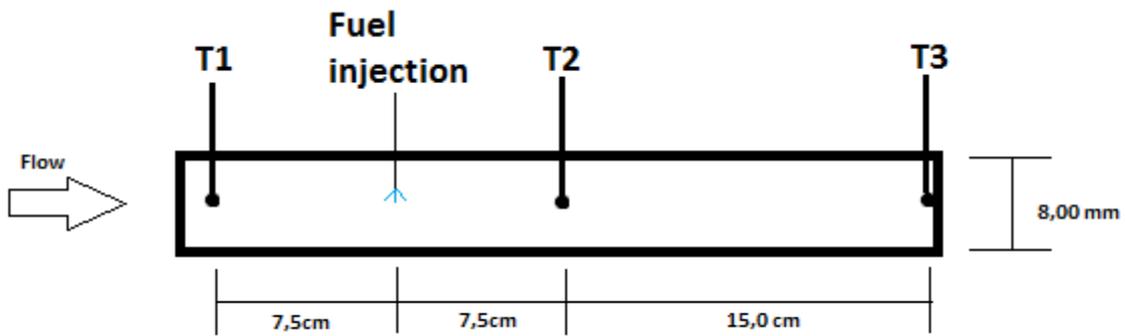


Figure 2. Test section setup

With these thermocouples, it was possible to get the air temperature before and after the ethanol injection, as well as verifying the thermal stability of the system. It was used a data acquirer to store all the data from the thermocouples. The data acquirer generates real time graphics “temperature *versus* time”, which shows the stability of the system.

For this preliminary test, the experiment was conducted in order to verify the requirements to completely evaporate the ethanol injected. Table 2 shows the equivalence ratio ( $\Phi$ ), it’s flows of air,  $V_{air}$ , and ethanol  $m_{comb}$ . As shown in figure 2, the length of the test section was fixed for preliminary test.

For each air flow, there will be a residence time of the mixture inside the test section. As the length is fixed for preliminary experiments, air flow will be the only residence time parameter. To calculate the residence time, it’s required the speed of the drop,  $V_d$ , and the length of the test section,  $L_t$ . The speed of the drop will be considered the same speed of the air, which can be calculated using Eq. 1. The length  $L_t$  will be considered the difference between ethanol injection point and the end of the Teflon line. These results are showed in table 2.

$$V_d = \frac{V_{ar}}{At} \quad (1)$$

Test N°	$\Phi$	$m_{comb}$ (g/s)	$V_{ar}$ ( $m^3/s$ )	$V_d(m/s)$	$L_t(c m)$	$tr$ (s)
1	0,7	0,01091	0,000278	3,5456	22,5	0,06346
2	1	0,01547	0,000275	3,5032		0,06423
3	1	0,0232	0,000413	5,2654		0,04273
4	1	0,03094	0,000552	7,0276		0,03202

Table 2. First test’s variables

Initially, the heater was turned on with its minimum power. It was started by testing the mixture with equivalence ratio of 0,7. It was checked which temperature was needed at the point of ethanol injection for the mixture to be completely evaporated. Consequently, the other parameters set in Table 2 were tested. When the ethanol wasn’t been fully evaporated, heater power was increased in order to get bigger air flow temperature.

For each heater power and mixtures tested, zero fuel flow was initially set, measuring the dry air temperature. As the heater has a very large thermal inertia, the graphics provided by the data acquirer (Figure 4) were used to verify the stability of all the three thermocouples, indicating the thermal equilibrium of the system. The temperatures before the ethanol injection point (T1), after the injection point (T2) and at the end of the test section (T3) were recorded. Then, ethanol was dosed at the rate indicated in the table 2. When the system stabilized, the temperatures were recorded and it was verified visually and graphically the full evaporation of ethanol.

To verify visually if there was liquid ethanol exiting the test section, it was used a cold plate made of steel placed in the end of the test section (Figure 3). Liquid ethanol carried by the air stream shocks with the plate, standing there until there was sufficient liquid ethanol to form a drop.

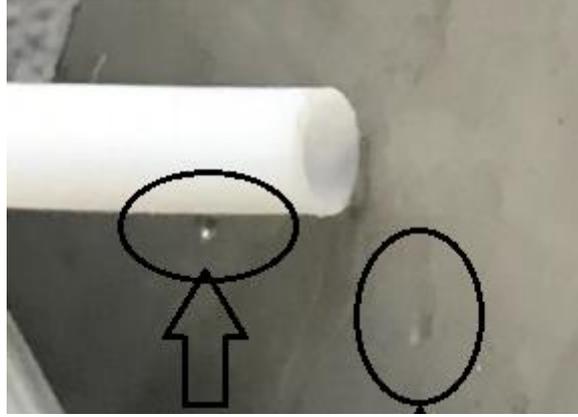


Figure 3. Liquid ethanol leaving the test section.

Also, it could be seen graphically if the ethanol was or wasn't all vaporized. During the tests, when liquid ethanol hits the thermocouple, it drops the local temperature in a short period of time, as shown in Figure 4. In this case, it is possible to see that there were many ethanol drops hitting the thermocouple T2, and after passing thru all the test section, some of the liquid ethanol couldn't evaporate, hitting the thermocouple T3.

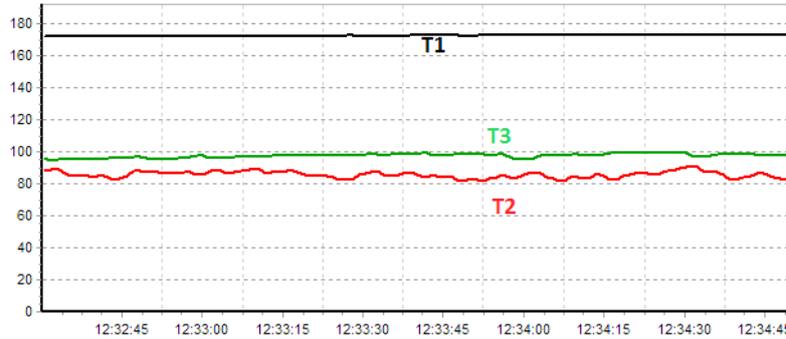


Figure 4. Liquid ethanol hitting the thermocouple T2 and T3. Temperature in Celsius (y axis) versus time (x axis)

A heat balance (Figure 5) can also be used to check the amount of ethanol vaporized. Considering that all ethanol leaves evaporated, all energy that enters the control volume must go out (equation 2), after the system stabilizes. If there isn't equality, an amount of liquid ethanol is leaving the test section.

$$\dot{m}_{air} \cdot h_{air\_in} + \dot{m}_{ethanol} \cdot h_{ethanol\_in} = Q_{conv} + \dot{m}_{air} \cdot h_{air\_out} + \dot{m}_{ethanol} \cdot h_{ethanol\_out} \quad (2)$$

To calculate  $Q_{conv}$ , equation 3 (Incropera et al., 2014) is used.

$$Q_{conv} = \dot{m}_{air} C_p (T_3 - T_1) \quad (3)$$

In the equations above,  $\dot{m}_{air}$ ,  $h_{air\_in}$ ,  $\dot{m}_{ethanol}$ ,  $h_{ethanol\_in}$ ,  $Q_{conv}$ ,  $h_{air\_out}$ ,  $h_{ethanol\_out}$  and  $C_p$  are, respectively, air flow rate, air enthalpy in the entry, ethanol flow rate, ethanol enthalpy in the entry, heat loss by the air after passing thru the test section, air enthalpy in the exit, ethanol enthalpy in the exit and specific heat coefficient for the air in and average temperature between T1 and T3.

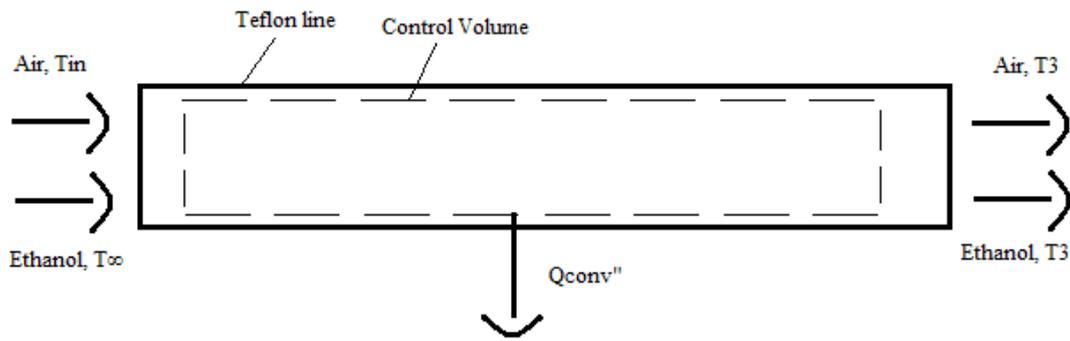


Figure 5. Heat balance over the test section

### 3. PRELIMINARY RESULTS

After measuring the temperatures for each Test N<sup>o</sup>, the minimum parameters were verified so that each mixture could be completely evaporated, according to Table 3. The temperatures are shown with or without the injection of ethanol (ethanol flow).

Figure 6 shows the stabilized situation for test N<sup>o</sup> 2, with ethanol flow. Ethanol is not evaporated at all in the beginning, because some of liquid ethanol hits the thermocouple T2, decreasing the local temperature. T3 shows a constant line, showing that during the residence time of the ethanol, all drops could be evaporated.

Test N <sup>o</sup>	$\Phi$	Ethanol flow	T1 (°C)	T2 (°C)	T3 (°C)
1	0,7	No	128	103,3	91,126
		Yes	128	94,6	86,4
2	1	No	185,5	139,3	130,5
		Yes	188,5	112,4	92,6
3	1	No	188,5	151,9	139,2
		Yes	182,3	105,2	112,7
4	1	No	212,1	179,8	165,6
		Yes	208,5	108	135,2

Table 3. Parameters to fully evaporate ethanol

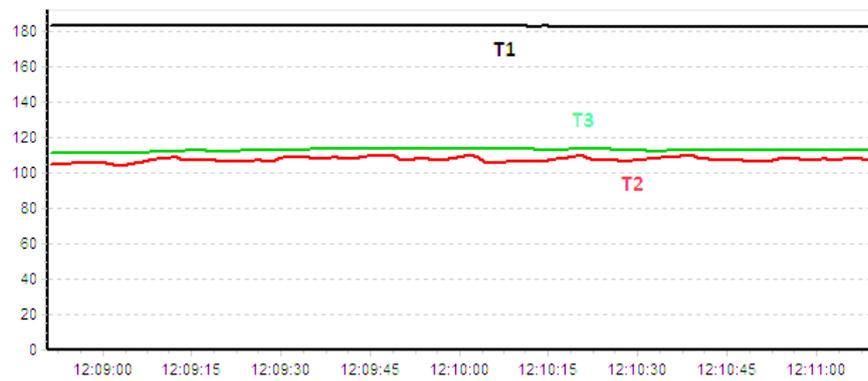


Figure 6. Evaporation of Test N° 2. Temperature in Celsius (y axis) versus time (x axis)

For each Test N°, equation 2 and 3 were also used to check evaporation. Considering  $T_{in}$  an average between T1 and T2, and  $C_p$  for an average temperature between T1 and T3, heat rate entering and leaving de control volume can be calculated. As the difference between the points are small, and taking account the measurement uncertainty, can be assumed that all ethanol was vaporized.

Test N°	Qin (W)	Qout (W)	Difference (%)
1	131,8	139,2	5,61
2	147,9	149,2	0,88
3	225	231,9	3,07
4	316,7	325,4	2,75

Table 4. Heats entering and leaving the control volume

#### 4. CONCLUSIONS

Fuel evaporation process has many parameters that have to be controlled. In this article, equivalence ratio and inlet air temperature have been discussed.

It was possible to verify the minimum requirements that have to be set in order to evaporate each ethanol flow, and also the different methods that can be applied to verify this evaporation.

For better results, some studies must be carried on. Different test section lengths have to be set in order to study better the influence of residence time, with constant air flow. Also, the system must have an isolation cover, in order to reduce heat lost by convection thru the Teflon lines, and then improve heat transferred to fuel.

#### 5. REFERENCES

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