



# Laminar burning velocity measurements using the Heat Flux method and numerical predictions of iso-octane/ethanol blends for different preheat temperatures



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## HIGHLIGHTS

- The laminar burning velocity has been measured with the Heat Flux method.
- Liquid fuels, namely iso-octane, ethanol and their blends, with air were investigated.
- With rising ethanol fraction, the laminar burning velocity increases.
- Measurements are compared to numerical simulations.
- Simulations cannot predict the exact value but the trend of the burning velocity.

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## ABSTRACT

The substitution of gasoline with bio-ethanol is an intended way to reduce the climate impact of the traffic sector. To extend the knowledge of fundamental flame properties of ethanol/iso-octane flames and improve the numerical predictions for the effect of ethanol blending in internal combustion engines, measurements of the laminar burning velocity of established blend ratios of ethanol and iso-octane were carried out and compared to existing numerical mechanisms. The measurements were carried out with the Heat Flux burner, with thermocouples of type E at the burner plate, which was adapted with an evaporation unit based on direct vaporization to investigate the liquid fuels. The preheating temperature ranges from 298 K to 373 K and the pressure is atmospheric. First measurements of the laminar burning velocity of ethanol/air and iso-octane/air flames were carried out for validating the system. A good agreement with available literature data could be achieved for the investigated equivalence ratios from 0.7 to 1.4. Furthermore laminar burning velocities of different iso-octane/ethanol/air blends, namely E10, E24, E40 and E85, are presented. Through variation of the preheating temperatures (298 K, 323 K, 348 K and 373 K) the temperature dependency could be analyzed. The uncertainty analysis of the measurements has been revealed. Numerical simulations were carried out using different chemical mechanisms for ethanol/air flames, iso-octane/air flames as well as various fuel blends and preheating temperatures and are compared to the experimental data. The agreement is evaluated through a classification of the discrepancy between both.

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## 1. Introduction

The CO<sub>2</sub> emission reduction through the utilization of bio-fuels has become, especially in internal combustion (IC) engines, of increasing concern. When considering gasoline engines this reduction is mostly reasoned by the increase of the octane number. This leads to a potential for the IC engine development by increasing

the compression ratio and thus raising the efficiency [1]. For spark-ignition engines renewable bio-ethanol is mainly used for blending and the European Union set a target for bio-ethanol blends for 2020 of 10 vol.% from currently 5.75 vol.% [2]. So nowadays, different blends of bio-ethanol with conventional fossil fuels are available. Table 1 gives an overview of these blends for commercial automotive applications in selected countries [2–4].

Numerical simulations are used to predict the various combustion characteristics in IC engines caused by the different ratios of bio-ethanol. The fundamentals of these simulations are chemical

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reaction mechanisms. These mechanisms are usually validated with characteristic flame properties such as the laminar burning velocity. For the pure substances, ethanol and iso-octane, several experimental data sets have been published, see [5–8]. However, only very limited data for common bio-ethanol blends, e.g. E10 and E85, and low preheat temperatures, e.g. 298 K, are available.

Within this paper experiments to obtain the laminar burning velocity of iso-octane/air and ethanol/air flames are carried out for validating the adapted Heat Flux burner set up with the vaporization system. Furthermore different iso-octane/ethanol blends mixed with air to achieve the equivalence ratio are provided at preheat temperatures reaching from 298 K to 373 K. A detailed uncertainty analysis is performed.

Iso-octane is used as the reference fuel for both the measurements and the simulations. This gives the possibility to point out the effect of ethanol blending in more detail whereby the investigated blends are chosen according to real existing ratios (Table 1). Furthermore an optimized reaction mechanism for iso-octane/ethanol blends as well as a common ethanol mechanism are evaluated in their ability to predict these laminar burning velocities.

## 2. Experimental method

In 1993, de Goey, van Maaren and Quax initially proposed the Heat Flux burner for measuring the laminar burning velocity [9]. The main advantage of this method is the investigation of an unstretched one-dimensional flame under quasi adiabatic conditions [10].

The main parts of the Heat Flux burner are shown in Fig. 1. The utilized burner in this work has a 2 mm thick brass burner plate with a diameter of 30 mm and a uniform perforation ( $\varnothing 0.5$  mm). The heating jacket sets the temperature of the burner plate 70 K higher than the temperature of the fuel–air mixture. A cooling jacket surrounds the plenum chamber and regulates the temperature of the mixture between 298 K and 373 K. In order to measure the radial temperature profile of the burner plate eight thermocouples of type E ( $\varnothing 0.5$  mm) are attached to achieve a high resolution and sensitivity.

With the measured temperature profile the direction of the net heat flux, which is based on the sum of the heat flux from the flame front to the burner plate and the heat flux from the burner plate to the fuel–air mixture, is determined. For gas velocities  $u_g$  lower than the laminar burning velocity  $S_L$  the net heat flux becomes positive and the burner plate achieves a higher temperature than the heating circuit. This causes a radial heat flux from the burner plate center to the edge. The net heat flux falls below zero when  $u_g$  is higher than  $S_L$ . In this case, the temperature at the center of the burner plate is due to the radial heat flux the lowest measured value. For a planar temperature profile, the net heat flux is zero and quasi-adiabatic flame conditions are achieved, which means that the gas velocity equals the laminar burning velocity.

To provide liquid fuels to the Heat Flux burner, different vaporization systems have been used in literature [8,11]. In [8] the liquid fuel is mixed with air as carrier gas and then vaporized in an evap-

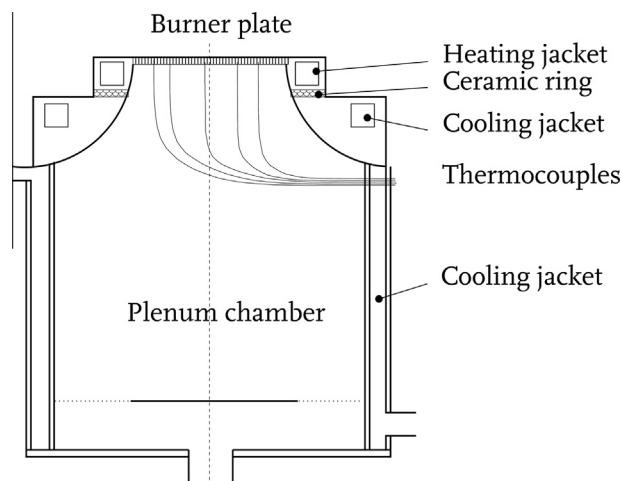


Fig. 1. The Heat Flux burner [22].

orator. Following, the evaporated stream is mixed by the appropriate amount of air to reach the intended equivalence ratio. In [11] the liquid fuel is supplied by an injector for gasoline engines and evaporated and mixed with air in a heated tube.

Another approach was developed for this work. The flowchart of the Heat Flux burner set up with the adapted evaporation unit is presented in Fig. 2. The major difference is the use of an adapted direct evaporator type aSTEAM from aDROP GmbH. Main advantages of the aSTEAM in this context are twofold: First, a pulsation free conversion of liquid into the gas phase can be achieved. After a short initial time of stabilisation, the output of steam equals exactly the liquid feed mass flow. This allows a dosing in the liquid phase, which can be done much easier than in the hot gas phase. The second aspect is based on the absence of any carrier gas due to the construction as direct evaporator. No spraying agent or other diluting gas needs to be added, simplifying the experimental control. The evaporation takes place in an evaporation matrix with a large surface. Together with a PID-controlled heating system, the evaporation zone is kept stationary, leading to the essential equivalence of in- and outgoing massflows. The working temperature has been adapted to 473 K to provide most stable operation in respect to the applied massflow and specific evaporation enthalpies. Investigations showed for this type of evaporators flow fluctuations of less than 1% of the set value if operated from rated flow down to 1/40.

Initially the liquid fuel is stored in a stainless steel tank and pressurized with nitrogen to 5 bar(g). A mass flow controller (mini-CORI-Flow™, Bronkhorst B.V.) based on the Coriolis effect controls the flow of the liquid fuel. During the pressure loss through the mass flow controller, the dissolved nitrogen separates from the liquid fuel. This nitrogen is eliminated before entering the direct evaporator to ensure a correct measurement. The adjusted equivalence ratio determines the air flow which is regulated by a thermal mass flow controller (EL-Flow®, Bronkhorst B.V.). In order to create a homogenous mixture of the vaporized fuel and air a mixing chamber, which prevents the condensation of evaporated fuel during mixing, is used. This fuel preparation and thermal conditioning system allows temperatures of the fuel–air gas mixture between 298 K and 373 K before entering the Heat Flux burner.

## 3. Quantification of experimental uncertainty

The calculation of the uncertainties based on the “Guide to the Expression of Uncertainty in Measurement” (GUM) [12] is carried out for the laminar burning velocity  $S_L$ , the ethanol volume fraction  $\varphi_E$  and the equivalence ratio  $\Phi$ . Here only major error sources are

Table 1  
Representative ethanol blends for automotive applications for selected countries.

Country	Ethanol blends
Austria	E5, E85
Brazil	E18–E25, E100
Canada	E5
Germany	E5, E10, E85
USA	E17, E24, E85
Japan	E3

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