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Impact of Magnetic Field on the Stability of Laminar Flame in a Counter Burner

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ABSTRACT

This study investigates the influence of magnetic fields on the behavior of Liquefied Petroleum Gas (LPG)/air mixtures, with a particular focus on the stability limits and flame temperature. The primary objective is to elucidate the impact of magnetic fields on the modification of premixed and diffusion laminar combustion within a vertical counter-flow burner. An integrated experimental setup, encompassing a counter-flow burner, an optical image system, an electromagnetic induction charger, and a digital image processing technique, was employed. This apparatus array enabled the capture of flame images across varying intensities of magnetic field and air/fuel ratios, thereby providing comprehensive data on both diffusion and premixed flames. A sophisticated image processing technique was utilized to delineate details concerning the counter flame front's geometry, including shape, area, and diameter. Acquired flame images were subsequently subjected to analysis using MATLAB software. Findings indicated a slight increase in flame temperature concurrent with the intensification of the magnetic field for both premixed and diffusion combustion. Notably, the presence of a magnetic field significantly enhanced flame stability across both flame categories. Furthermore, the flame disk operating area demonstrated a proportional expansion with the magnetic field intensity, with a more pronounced effect observed at 5000 gausses in the diffusion flame as compared to its premixed counterpart. In conclusion, this investigation underscores the pivotal role of magnetic fields in augmenting flame stability, offering valuable insights towards optimizing combustion processes.

1. INTRODUCTION

The development of combustion tools for power generation is fundamentally contingent on an understanding of key parameters, including flame stability, emission characteristics, self-ignition, and combustion dynamics. These parameters are largely governed by the properties of the fuel/air mixture [1], which envelop factors such as flame speed, ignition delay, minimum ignition energy, and flammability limits [2]. The burning velocity of premixed and diffusion flames within the necessary mixing ratio ranges is a critical feature in the design of flame generators and industrial burners [3]. Moreover, flame stability is integral to flame aerodynamics, given its crucial role in conserving electrical and thermal energies within industrial burners [4]. The energy field generated by thermal sources is known to be influenced by the interaction with magnetic energy, with the magnetic properties of materials playing a critical role in the outcome. Magnetic fields, in turn, originate from the orderly arrangement of small regions termed as magnetic domains.

Numerous studies have been conducted to investigate the potential of magnetic fields to enhance the combustion process [5-7]. Investigations have included experimental studies on the influence of magnetic fields on propane and acetylene diffusion flames utilizing an electromagnetic system [8, 9]. These experiments incorporated magnetic fields of varying frequencies and duty ratios, established in a square waveform, with a maximum intensity and gradient of the magnetic field being 1.3 T and 0.27 T/mm respectively. The findings demonstrated a reduction in flame front height by up to 4.5% and an increase in brightness by up to 25% upon the application of a magnetic field. In a study by Wu et al. [10], the impact of magnetic fields on various characteristics of laminar diffusion flames of methane on a co-annular burner was examined. The results suggested a decrease in flame height and an increase in temperature in response to an escalation in the magnetic field.

Premixed flames, characterized by a thorough mixing of fuel with an oxidant such as LPG and air, require an energy source, typically a spark or small flame, for ignition. This initiates a self-sustaining flame around the ignition point, which propagates in all directions. However, the flammability of air and fuel mixtures is contingent upon the type of fuel and oxidant [7]. In contrast, diffusion flames occur at the interface of fuel vapor and air, where the fuel vapor and the oxidant remain separate prior to combustion. Dominated by the blending process, which is driven by molecular diffusion, a relatively slow procedure, diffusion flames are characterized by high temperatures produced when thermal energy is released, consequently accelerating the diffusion rate. Unlike premixed flames, diffusion flames only exist at the fuel-air interface, thus they lack an equivalent of burning velocity, flammability limits, or rich or lean mixtures [11-13]. Diffusion flames can generally be categorized into laminar and turbulent [14]. While laminar diffusion flames are characterized by slow-burning diffusion, such as in candle flames, turbulent diffusion flames, common in industrial burners, are created when fuel is sprayed or jetted into the air at a high velocity, inducing turbulence [15-17]. The resultant large interface area, rather than the molecular diffusion rate, determines the mixing rate in the turbulent case [18-21].

Though numerous studies have attempted to enhance the combustion process via external influence, existing literature suggests that only a non-uniform magnetic field can interact with the flame. The magnetic field appears to affect a small laminar diffusion flame more than a premixed or partially premixed flame. The mechanism of magnet-flame interaction is hypothesized to be due to the magnetic paramagnetism of oxygen in the air, which diffuses into the flame. However, the combustion characteristics of the flame subject to the influence of the magnetic field, particularly with respect to flame stability, are not fully understood. Consequently, the present work reports experimental findings on the stability of a laminar flame under the influence of a magnetic field in a counter-flow burner.

2. EXPERIMENTAL IMPLEMENTATION

The experiments employed a counter-flow burner, images optical system, electromagnetic induction charger, and digital image processing technique. These systems were used to collect flame images at various air/fuel ratios and various values of magnetic field intensity, providing information on diffusion flame and premixed flame. The experimental system was housed in an environment suitable for collecting flame data through an optical system, as all experiments were within the combustion laboratory at the Energy and Renewable Energies Technology Center at the University of Technology-Iraq. An image processing technique was used to collect the information for the counter flame front's shape, area, and diameter. MATLAB software was used to analyze recorded flame images. The apparatus components are illustrated in Figure 1.

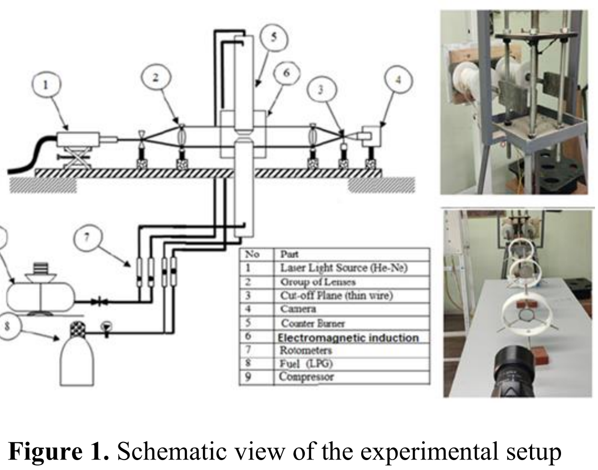


Figure 1. Schematic view of the experimental setup

2.1 Counter-flow burner setup

The counter-flow burner used in the current experiment includes two counter copper tubes with 26 mm diameter, reduced at the end to an outlet of 16 mm diameter. These burners were fixed by a structure made of steel. Distances between the outlet of the burner could be changed. The fuel and air for each burner side are mixed in the mixing chamber to form a premixed flame and pass fuel from the bottom and air to the top to form a diffusion flame. Four gas flow meters were used to measure the flow rates for LPG and air, with metered individually (± 1.1% accuracy) during the experiments. The calibration of such reactant flow meters at the mass flow controllers exit was conducted utilizing a RITTER Drum type (enable a measuring accuracy of ± 0.2% at a standard flow rate and approximately ± 0.5% over the whole measuring range). Air and LPG were fed to the combustion zone at room conditions of 1.0 atm and 303 K. The gas flow and airflow were controlled to permit wide volumetric mixing ratios.

2.2 Electromagnetic induction system

Several researchers have used an electromagnetic induction (EMI) system to measure the combustion process's characteristics [1]. The EMI components include a DC power supply, an excitation coil, a signal analyzer, and a Tesla meter. The system arrangement is shown in Figure 2. The excitation coil is an electromagnetic charger supplied by the DC power supply within a voltage range of 0 - 32 V and 0 - 100 Amp current range. This electromagnetic charger comprised a U-type yoke and two coils wound with 350 turns of enamel-coated, 1.5 mm diameter copper wire. The coils were connected in a parallel pattern within the electrical circuit to produce a variable intensity magnetic field intensity. The yoke was made of steel to reduce the loss by eddy current. The cross-section areas of the yoke poles were 22.0 mm, perpendicular to the flow direction: x-axis, and 60.0 mm, parallel to the flow direction, to grip the entire test section. The Tesla meter sensors were fixed between the yoke poles and the test section to measure the magnetic flux. The excitation coils measure the magnetic field intensity from 0.0 to 5000 gausses. Initial tests were accomplished to reveal the magnetic field intensity distribution between the excitation poles.

2.3 Digital image processing

Image processing is common in studying combustion processes and flame propagations by detecting the flame front boundaries [2, 3]. The use of a simple detection technique is unreliable due to a low contrast ratio along the frontal borders of the flame, as they need to be properly visible at the edges of the flame. In contrast, the Image Processing technique can detect the frontal border of the flame using digital image processing of the raw images, making the frontal edge analysis more accurate and visible. A software program was developed in a MATLAB environment to extract information from the recorded flame image data. The MATLAB-developed code depends on flame front image frames for data analysis and measuring flame parameters, including diameter, area, and spatial location.

Several steps were undertaken to determine the flame front parameters, including background extraction and noise reduction, binary image and thresholding operation, and morphological operations on the binary image. The erosion and dilation method were utilized in the digital image processing of the current measurements. The number of pixels added or removed from an image depends on the size and shape of the structuring element used to process the binary image. Therefore, it could modify the flame front's size and shape. However, combining these operations maintains the same flame size. Figure 3 shows the image processing steps. The images of the flames front were used in the next step of quantitative analysis, such as measuring the equivalent diameter and area of the flame disc.

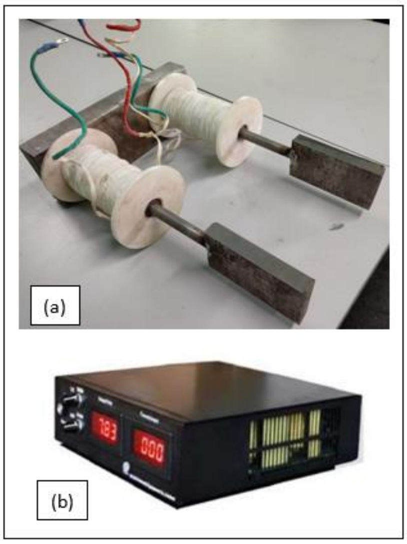


Figure 2. Electromagnetic induction system (a) EMI components include a DC power supply, an excitation coil, a signal analyzer; (b) a Tesla meter

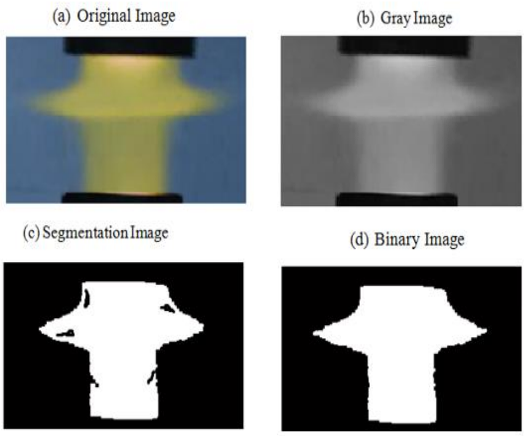


Figure 3. Image processing procedures

2.4 Experimental procedure

Air and LPG have been decided as mixtures at various ratios. The first set of experiments was conducted with a counter-flow burner arrangement. Several diffusion flame images of different air and LPG flow rates with varied magnetic field intensity have been captured, as mentioned in Table 1. Then, the premixed flame images of air/LPG equivalence ratios (0.61 < φ < 1.33) (lean fuel mixture side for equivalence ratios from 0.61 to near 1.0, while rich mixture side for equivalence ratios from up 1.0 to 1.33) with varied values of magnetic field intensity were recorded, as mentioned in Table 1.

Flame stabilization was known to keep the flame front fixed on burner edges. Firstly, the blow-off limit represents the start to separate the flame front from the burner edge and extinguish it. Secondly, the flame disc region is where the flame front (flame disc) is fixed on burner edges. Thirdly, double flame disc is when the flame front comprised two discs focusing near nozzle edges for counter burners. Depending on limited critical theory for speed drop, the velocity gradient, g, at blow-off limit and disc flame limit was calculated from measuring the unburnt gases flow rate [1]:

$$g = \frac{8V_o}{Dt} \quad (1)$$

where, V_o is the unburned gas velocity and Dt is the burner pipe diameter.

Table 1. Data collection for the effect of magnetic field intensity on counter-flow burner flames

1st Set	Diffusion Flames
Air flow rate (SLPM)	40-82
LPG flow rate (SLPM)	9-34
Magnetic field intensity	0, 1000, 3000, 5000 gausses
Distance between magnetic poles	150, 180, 220 mm
2nd Set	**Premixed Flames**
Air flow rate (SLPM)	42-93
LPG flow rate (SLPM)	10-36
Magnetic field intensity	0, 1000, 3000, 5000 gausses
Distances between magnetic poles	150, 180, 220 mm

3. RESULTS AND DISCUSSION

The results are presented as a comparison between the measurement of the disc flame and the double flame front. The comparison parameters included the variation of flame stability limits and profile at various equivalent ratios and temperature distributions in the front of the flame of premixed and diffusion flames.

3.1 Analysis of flame stability limit

Experiments showed that any increase in the flow rate of LPG and the airflow rate leads to a discrepancy in the stability limits of the flame front, as shown in Figure 4. The limits of the stability of the flame front are determined within two basic limits: the blow-off limit and the double disc limit. In contrast, the region of the flame disc is determined by considering it is the ideal burner working area. These results also agree with the experimental tests of Wahhab [1].

Several experiments for the velocity gradient over the range of equivalences ratio for a lean and rich side under the effective magnetic field 5000 gausses were performed to test the stabilization behavior of premixed and diffusion flames. The results are presented in Figure 5. The presence of a magnetic field shows a strong effect on flame stability enhancement. As shown in Figure 5a, the value of stability limits for the premixed flames strongly changed with the increased magnetic field. In other words, the flame disk operating area increased with increasing magnetic field intensity at 5000 gausses. Also, Figure 5b shows that the value of stability limits for the diffusion flames increased when noticing the flame disk operating area with magnetic field intensity increasing to 5000 gausses.

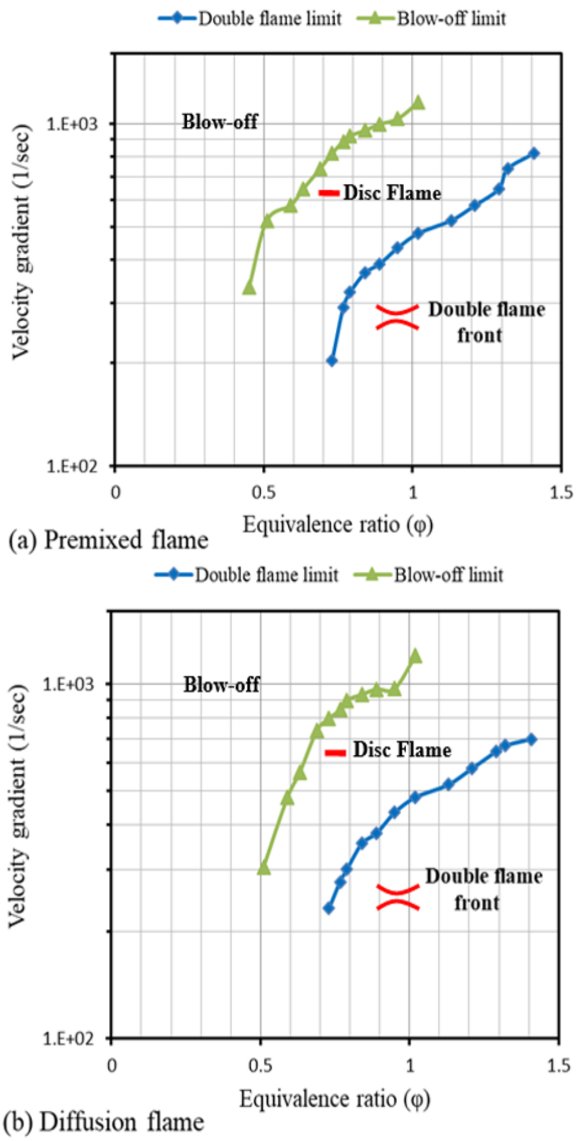
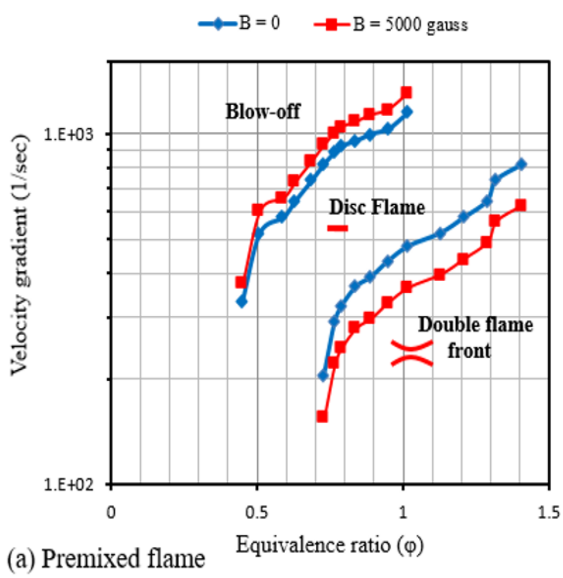


Figure 4. Variation of stability limits for LPG/air mixtures; (a) premixed flame and (b) diffusion flame



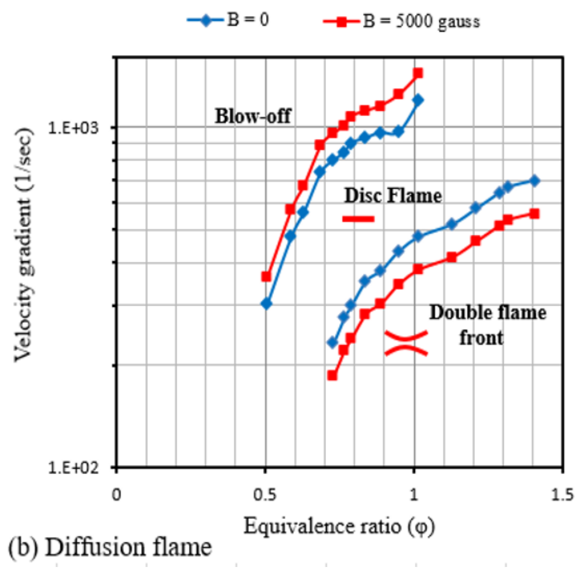


Figure 5. Stability limits profile of premixed and diffusion flames with effect magnetic field intensity 5000 gausses

3.2 Analysis of temperature distribution

The effect of the magnetic field on the flame temperature at premixed flames was achieved by comparing the case of no magnetic field and with the magnetic field at intensities of 1000, 3000, and 5000 gausses at equivalence ratio φ = 1.02. The measurement results are presented in Figure 6. The flame temperature recorded increases with the effected magnetic field when the collected data are compared with increased magnetic field intensity up to 5000 gausses. At the same time, these value increases remained little changed after the temperature correction. These results also agree with those obtained from the experimental tests of Mola et al. [2].

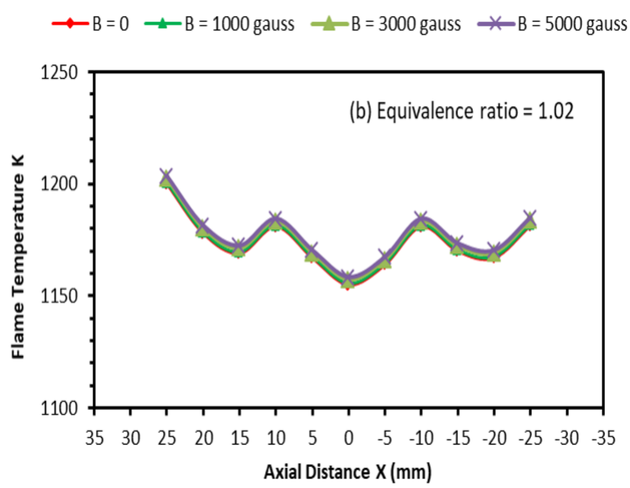


Figure 6. Variation of flame temperature premixed flame with axial distance in a central location between burner edges at φ = 1.02

The results are shown in Figure 7 for the case of diffusion flame. Applying a magnetic field at an equivalence ratio φ = 1.01 shows no significant changes in axial temperature. Relatively smaller temperature variations appeared for an equivalence ratio of 1.01. A temperature increases of approximately 50°C occurs at mid-point positions between the burner edges, increasing the magnetic field to 5000 gausses.

The reason is that the temperature of the magnetized fuel becomes lower than that of no magnetic field in the soot formation region. This observation for the current experiment occurs at 10-15 mm above the burner exit. The results obtained for the temperature of the diffusion flame were compared with the experimental results from the study [17] for flames within the equivalent ratio of 1.0 with values of the same range of the effective magnetic field intensity. The comparison showed agreement between the temperatures of the spreading flame, as shown in Figure 8.

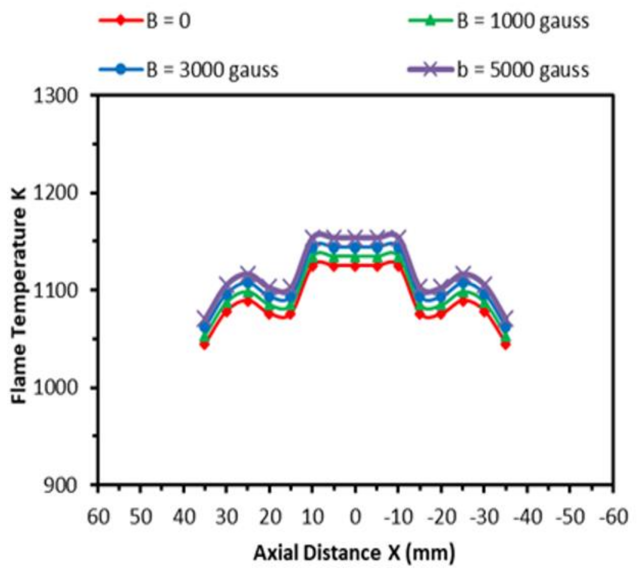


Figure 7. Variation of flame temperature diffusion flame with axial distance in mid location between burner edges at φ = 1.01

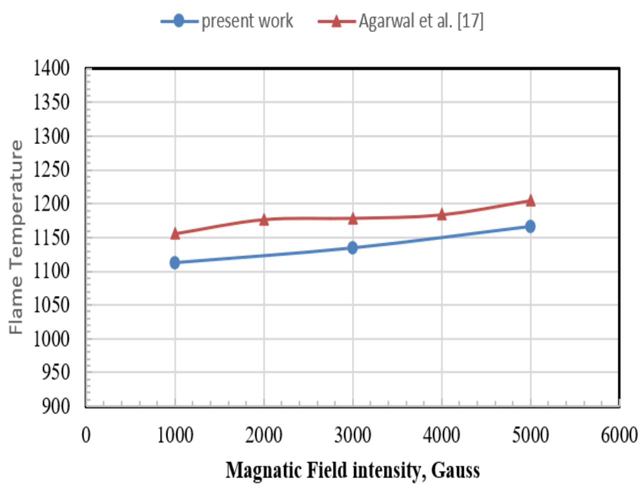


Figure 8. Comparison of the flame temperature of diffusion flame with Agarwal et al. [17] at φ = 1.0

4. CONCLUSION

The effect of the magnetic force caused by the magnetic field applied to the LPG/air mixtures on burning velocity, flame temperature, and stability limits is studied experimentally. The experiments employed a counter-flow burner, images optical system, electromagnetic induction charger, and the digital image processing technique. These systems were used to collect flame images at various air/fuel ratios and various values of magnetic field intensity, providing information on diffusion flame and premixed flame. An image processing technique collected information for the counter flame front's shape, area, and diameter. MATLAB software was used to analyze recorded flame images. The results demonstrate that a magnetic field strongly enhances flame stability. The flame temperature results were not recorded as large, increasing with the effected magnetic field for both premixed and diffusion combustion. For premixed and diffusion flames, the flame disk operating area increased with increasing magnetic field intensity to 5000 gausses in diffusion flame more than premixed flame. This work recommends recording the effect of a magnetic field on combustion characteristics for premixed and diffusion flames. Further study of the influence of magnetic field on combustion characteristics for other gaseous fuels such as methane and propane to study the effect number of carbon atoms and explore the extent of its effect on the stability limits.

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NOMENCLATURE

V_o	Unburned gas velocity (m/s)
Dt	Burner nozzle diameter (mm)
φ	Equivalence ratio
g	Velocity gradient (1/s)
B	Magnetic intencity (Gauss)
Va	Air flowrate (l/min)
Vf	Fuel (LPG) flowrate (l/min)