Meter for the measurement heat of combustion

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Abstract

This paper presents a proposal of a thermal instrument intended for the evaluation of heat energy of fluid fuels. Two thermal devices the flowmeter and the combustor are the basic components of the instrument. The meter maintains a constant temperature in the vicinity of the combustion zone. The amount of heat energy in the fuel is calculated as the ratio of the electric power change expressed in Watts to the change of fuel supply delivered to the combustor within a time period of 1sek. The method enables a direct evaluation of fuel energy expressed in Jules per unit of mass or volume. For some applications, the meter may be a good alternative for a bulky bomb calorimeter.

Keywords: thermal sigma delta modulator, mini combustor, platinum resistor, aluminum nitride

Introduction

Fluid fuels are widely used for powering motors, heating and cooking. The possibility of verifying the quality of fuels is of paramount importance, because fuel quality directly influences consumption, and this has an influence on customer charges. On the other hand, evaluation of the quality of fuels, especially fuel heat energy, is a long and time consuming process, which can be completed at a laboratory site with a specific equipment. The proposed combustion sensor an the flowmeter can be a foundation for construction of simple portable instrument, which can be considered as an alternative to the expensive and bulky bomb calorimeter.

1. Method of measurement

The principle of measurement is explained in Fig. 1. A small volume stable flame is maintained between two ceramic plates, whose temperature is being controlled by two thin film platinum resistors deposited on both ceramic plates. These resistors serve as heaters and temperature sensors. The resistors are connected to electronic circuitry, which maintains a constant temperature of both ceramic plates regardless of external or internal conditions. It is also assumed that both ceramic plates display sufficiently high thermal conductivity that the same single value of temperature can be considered for each small portion of both ceramic plates. The temperature of both ceramic plates is maintained at a constant temperature above 800°C. The high temperature of the combustion zone is essential for performance, because the flame is not quenched in the vicinity of the hot ceramic plates and thus a stable burning process can be maintained very close to the ceramic plates, so the heat exchange factor can be improved. The intensity of fuel supply is controlled by a fast response precision thermal flowmeter.

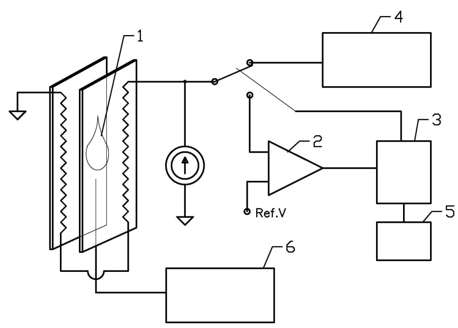

Fig. 1. The principle of measurement. 1- flame, 2- comparator, 3- switch driver, 4- power supply, 5- clock, 6-fuel supply controller.

As the additional amount of fuel enters the combustion zone and is being burned, an additional amount of heat is produced. That heat flux, mostly in the form of infrared radiation, is absorbed by the ceramic plates. In response, in order to maintain the constant temperature of the ceramic plates, the control circuit decreases the amount of electric power delivered to the heaters. On the basis of the correlation between the electric power delivered to the heaters and the intensity of fuel supply fuel the heat energy of the fuel is evaluated. The amount of heat energy in the fuel is calculated as the ratio of the electric power change expressed in Watts to the change of fuel supply delivered to the combustor within a time period of 1s. In this way, the method enables a direct evaluation of fuel energy expressed in Jules per unit of mass or volume.

2. Basic measuring devices

The thermal flowmeter and heat combustion sensor are the basic devices of the instrument. Both devices use the same principle of measurement, which is called a constant temperature principle. In order to obtain a rapid response, the same platinum resistors serve as heaters and temperature sensors. In both devices, the process of temperature control is accomplished by switching the heaters to a constant voltage synchronously with a clock frequency

2.1. Flowmeter

Thermal devices are sometimes seen as electric circuits, - where thermal resistance is seen as electrical resistance, - temperature difference as voltage difference and heat flux is seen as current. Following the principles of Wheatstone's bridge, a thermal bridge structure for flow intensity measurement was designed, which is presented in Fig. 1. If the bottom of thermal bridge structure is connected to the heat sink and constant electric power is delivered to both resistors at the top a constant temperature is established along the ceramic plate.

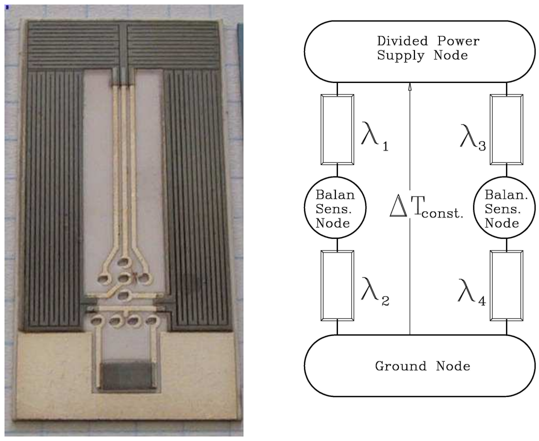

Fig.1 Ceramic structure of thermal bridge, and its schematic representation (on the right). Contrary to electric bridge, thermal resistances are distributed and the power supply nodes as well as the sensing nodes occupy large areas. The bridge structure is stable because the four thermal conductances are made with the same homogenous material,.

The measured fluid is guided between two identical plates as shown in Fig. 1 through the “U” shaped channel along the four resistors deposited on ceramic plate. As fluid moves towards the area of higher temperature it acquires heat from the ceramic structure, and provides heat to the ceramic plate as it moves towards an area of lower temperature. A constant temperature distribution in the ceramic structure, regardless intensity of fluid flow, is maintained by long balancing resistors which compensate the heat flux changes caused by the moving fluid. Due to the large area of the compensating zones the heat exchange fluxes are proportional to fluid flow intensity. The flow sensor operates as a self-balancing thermal bridge. The process of balancing is performed sequentially (adjustment - verification - adjustment - verification...) in small steps corresponding to the power of the least significant bit. That method of temperature control is called thermal sigma delta modulation [3, 4].

A simplified block diagram of thermal sigma delta modulator intended for thermal bridge is displayed in Fig. 2

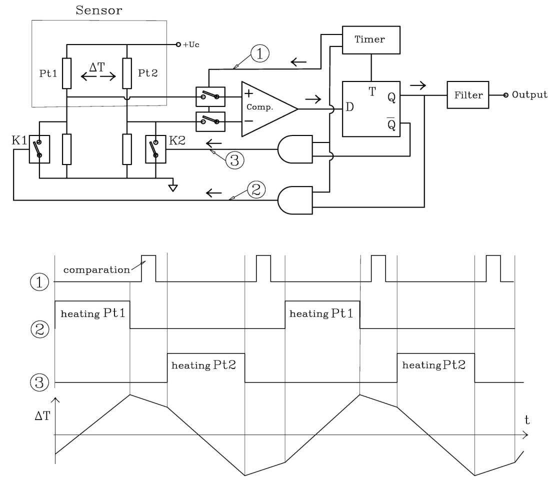

Fig. 2 Symmetrical thermal sigma delta modulator. The process of temperature comparison is performed during the short time interval when both switches, K1 and K2, are off. During the heat pulse, when the comparator is disconnected, a procedure off input offset cancellation is executed in the comparator circuitry.

The thermal sigma delta modulator is functionally analogous to the first order electronic sigma delta modulator [5]. The only difference exists in the comparator sub-circuit, while an electronic modulator uses a standard voltage comparator, in the thermal device a temperature comparator is required. In our case, this was accomplished with thermal sensing resistors combined with an analogue comparator.

It can be noticed, that the measuring legs of the thermal bridge, which occupy the area covered by the balancing resistors, - contrary to the electric equivalent, - are not thermally isolated. This fact does not have a significant influence on performance, because if the bridge is balanced, there is no temperature gradient in the horizontal direction, so there is no heat transfer in the horizontal direction. Thus, both legs can be considered as thermally separated. Fluid, after entering the thermal bridge, acquires the heat as it moves, alongside the first bridge leg towards the main heater, and discharges heat while it moves towards the heat-sink, alongside the second bridge leg. In order to maintain thermal bridge balanced the heat transferred by moving fluid must be compensated by film balancing resistors deposited on the legs. The process of balancing is executed sequentially in two steps: temperature comparation and single heat pulse compensation. Both processes are repeated with a frequency of 10 kHz. This method of balancing ensures that the bridge is always balanced or unbalanced with a precision of the half compensating heat pulse. If there is no fluid move, there is no heat transfer, and, in a given time period, an equal number of heat pulsed is provided to both legs of the thermal bridge. As the fluid moves a higher number of heat pulses must be provided to one leg and a lesser number to another. The difference is linearly proportional to flow intensity. It has to be noted that this sensor-converter is not provided with a filter. Before displaying a digital output signal, it requires digital filtering. The readout module performs the necessary digital processing.

Perception of the sensor-converter from the thermal bridge perspective exposes its advantages as well as disadvantages. The structure can be considered as stable, because the main thermal conductors are made within the same homogenous piece of ceramics. Also, thermal conductance between the heating resistors and components of thermal bridge are secure and low due to the large surfaces of the film resistors. The thermal bridge perspective also reveals the weak point. Thermal contact between the ceramic structure and the heat-sink must be extremely stable, because any change of local thermal conductivity within the area where the ceramics exchange heat with the heat-sink influences the bridge balance. It is also apparent that the thermal conductance of ceramics between the heat-sink and the main heater establishes the scale of the sensor.

Correlation between flow intensity and the number of output pulses can be expressed by the formula [6]:

$$\upsilon = \frac{1}{s_H \cdot \rho} \cdot \frac{L}{K} \cdot \frac{R_G}{R_B} \cdot \frac{\Delta m}{m} \qquad (1)$$

where:

- fluid flow intensity [ccm/s],

s_H – fluid specific heat [W/deg ccm],

ρ - fluid density [g/ccm],

L - thermal conductance between main heater and heat sink [W/deg],

R_G - resistance of main heater,

R_B - resistance of balancing resistor,

m - number of clock pulses in period of 1s,

m- difference of heat pulses delivered to the left and to the right branch in period of 1s, K - heat exchange factor between fluid and bridge structure.

Noise reduction was accomplished by digital processing. In our application an advanced averaging was applied, for which the output signal can be described as follows:

if:

$$\left(Y[(n-1)\cdot t] - X[n\cdot t]\right) \le 0.025\cdot FSR,$$

then:

$$Y[n\cdot t] = 0.9\cdot Y[(n-1)\cdot t] + 0.1\cdot X[n\cdot t],$$

else: $$Y[n\cdot t] = X[n\cdot t]$$

where:

$Y[n\cdot t]$ - filtered output digital signal

$X[n\cdot t]$ - current output digital signal

$Y[(n-1)\cdot t]$ - preceding filtered output digital signal

FSR - full scale range

This approach provides precision readings (0.2% of F.S.R.) for slowly changing flows and enables recording of fast flow changes with reduced accuracy (2.5 % of F.S.R.).

The flow sensor with the thermal sigma delta modulator features an inherent high linearity and shows fast response to steep flow intensity changes.

Fig. 3 shows digital records of (90% FSR) steep flow changes. The readings were captured with a repetition rate of 10 Hz. The plots at the top and bottom of the central plot display the corresponding values in an extended scale. The plot shows the benefits as well as drawbacks of the applied noise reduction method.

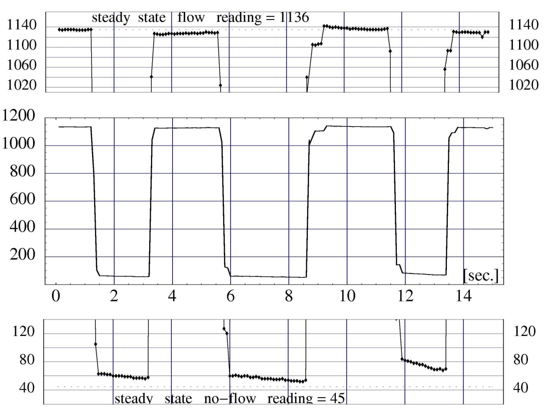

Fig. 3. Digital records of steep (90% of FSR.) flow intensity changes.

Linearity

Usually in order to carry out the linearity test, specific equipment is required. This flowmeter owing to its ability of completing fast measurements, can perform a linearity self test.

The linearity test is similar to a series of voltage measurements across capacitance, which is being discharged via the resistor. After matching the coefficients, for the scale, the time constant and the offset the theoretical plot can be evaluated. Next the difference between the measured values and the theoretical plot are accessed.

For the linearity test, a bottle with a 2-litre capacity was filled with nitrogen to a pressure of 15 psi. In order to ensure laminar flow, the bottle was discharged through a 1m long thin pipe (ϕ ≅ 0.4 mm). For this case (Reynolds number <1000), the flow resistance [2] defined as the ratio of pressure drop to the volume of gas discharged within a time period of 1 s. can be expressed as:

$$R_F = \frac{128}{\pi}\cdot \mu \cdot L \cdot D^{-4} \qquad (2)$$

where:

μ - dynamic viscosity,

L- length of a pipe,

D- inside diameter of pipe.

Hence, the flow intensity readings during discharge should comply with the formula:

$$\upsilon(t) = (\upsilon_{FS} - \upsilon_{off})\cdot e^{\frac{-t}{R_F\cdot C}} + \upsilon_{off} \qquad (3)$$

where:

R_F - flow resistance through the pipe,

C - bottle capacity,

υ_{FS} - initial flow intensity reading,

υ_{off} - offset reading (flow off).

After switching the gas flow through the flowmeter the readings were captured with a repetition rate of 2Hz. The recorded data was compared with the matched theoretical discharge curve, which are both shown in Fig. 4 (at the top). The difference between measurements and the matched exponential plot is shown in Fig. 4 (at the bottom plot).

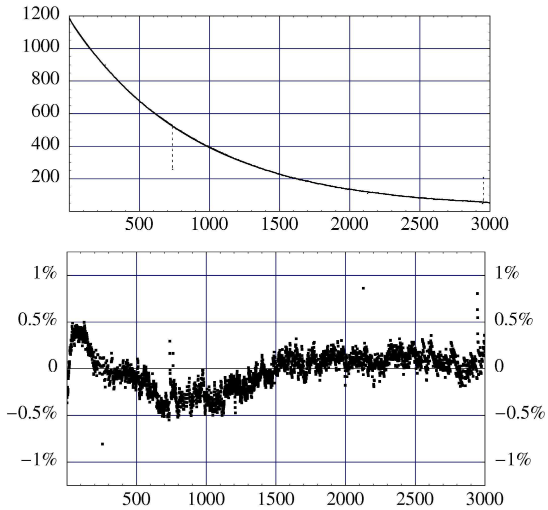

Fig. 4. Linearity test. The experimental data was compared with the matched theoretical curve (both overlapped on the top plot). Difference expressed in % of FSR is shown in the bottom plot.

2. 2. Syringe pump motor driver

The syringe pump module contains a thermal flow-meter with a thermal sigma delta modulator and electronic circuits which interfaces the flow-meter, step motor and computer. The advantage of this solution is the simplicity and fast response to steep flow intensity changes.

The syringe pump driven by a stepping motor is one of the means to supply liquids into micro analytical systems. The main advantage of this pump is low cost resulting from its simplicity. A constant speed of the driving stepping motor does not guarantee a constant flow of liquid because gases dissolved in the liquid can gather in some areas of a conduit and create bubbles. The bubbles become obstacles in the way of flow of liquid. They also operate as gas reservoirs, which, by compressing or decompressing, disturb the flow liquid. A syringe pump, which is controlled by a sensor-converter, can minimise these problems. Due to the feedback between the sensor-converter and a syringe piston driven by a stepping motor, the syringe piston goes back and forth and enables fluid acceleration as well as deceleration.

The block diagram of the syringe pump driver is displayed in Fig. 5.

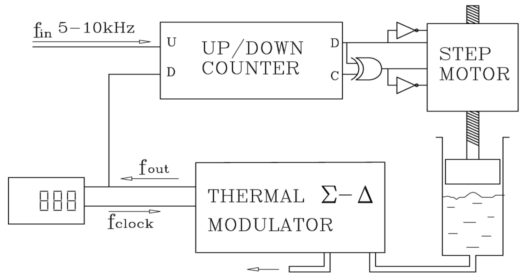

Fig. 5 Digital up-down counter serves as 2 phase step motor driver.

The up-down counter serves as a comparator, where the input signal, which sets the flow intensity, is compared with the output signal from the flowmeter. An up-down counter with additional logic also provides suitable power signals for driving the small step motor.

The flow sensor-converter provides the output signal as a train of “1” and “0”, where “1” stands for one heat pulse provided to the first leg of the thermal bridge, and “0” stands for one heat pulse provided to the second leg of the thermal bridge. If the fluid is not moving through the sensor-converter the output signal frequency is close to 5kHz. As flow intensity increases, it increases the output frequency.

Due to a feedback loop there is a correspondence between the signal, which sets the fluid flow, and the output signal from the sensor-converter. The correlation can be expressed as:

$$\left(f_S - f_O\right)\cdot\frac{V_P}{N} = f_O \cdot V_S \qquad (4)$$

where:

f_S - stands for the frequency of the input signal, which sets the fluid pumping speed,

f_O-stands for sensor-converter output frequency,

V_P- specifies the volume of fluid pumped by one step motor rotation,

V_S-specifies the volume of fluid which corresponds to one heat pulse of the sensor-converter,

N - specifies the number of pulses at the input to induce one step motor rotation.

The formula [4] can be rewritten:

$$f_S = f_O\left(1+\frac{N\cdot V_S}{V_P}\right) \qquad (5)$$

Because $V_P >> N^*V_S$, $f_S \approx f_O$

The ratio: $\frac{V_P}{N \cdot V_S}$ can be considered as the gain of the feedback loop. The gain can be established by up/down counter or mechanical transmission. Due to cyclic compensation, and high gain the piston goes back and forth, and the required flow is being established as a product of positive and negative moves after a large number of cycles.

Observed quasi smooth piston move.
The feedback response to the small flow change can usually be accomplished just within one clock cycle (100μs). The only element in the feedback loop, which demonstrates the inertia is the rotor of the stepping motor, because the step motor is not able to complete a full step in such a short period of time. Nevertheless, it was noticed, that at some properly fixed pumping pressures almost smooth fluent transitions between the following step motor positions, can be observed.

The syringe driver works fine when liquid is pumped under significant pressure (>0.5 bar, preferably >1bar), because at that condition loosen mechanics can be fixed by constant mechanical tension. A small gas reservoir between the fluid and the piston is advantageous and works as a gas cushion, which separates the fluid from mechanical vibrations.

2. 3. Heat of combustion sensor

The mini combustor, shown in Fig. 6 was created on a 50mm long and 10mm wide alumina strip on which a ceramic structure with channels and cavities was created. The channels guide the fuel and oxidant and via, multiple endings, provides them to the combustion zone. The channels were made with the application of ceramic green tape (FODEL). The green tape was laminated to 96% alumina plate. The green tape was dried at 750°C, next a network of micro-channels was created by laser machining, then the structure was prefired at 800°C, and in the next step it was covered with the following green tape layer of ceramics. After bonding a small additional alumina plate a 10mm long notch was created trough both alumina plates. The notch forms a cavity for the combustion chamber. The notch, which forms a combustion chamber on both sides, is overshadowed by two ceramic plates made of aluminium nitride.

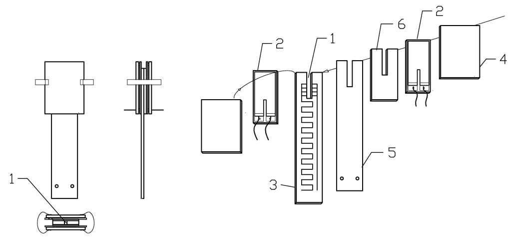

Fig. 6. Mini combustor. 1-combustion chamber;2-ALN plate with paltinium heater; 3-alumina plate with FODEL shaped channels;4-fused silica plate, 5- LTCC, 6- alumina plate.

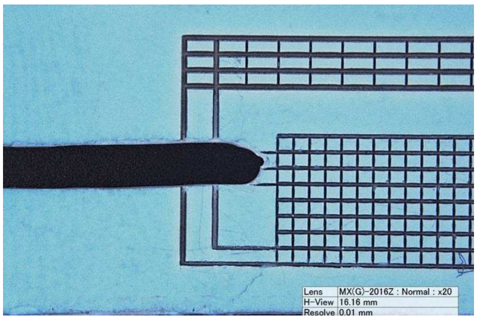

Fig. 7. Notch (1,5 mm wide) in the ceramic plate forms the combustion chamber. The fuel and oxidant are provided from opposite directions.

The ceramic plates made of aluminium nitride provided with platinum resistors serve as heaters and temperature sensors. Owing to high thermal conductivity, these plates also serve as heat spreaders, which ensure uniform temperature distribution in the vicinity of the combustion chamber, and in this way they provide safe conditions, for those parts made of alumina, for operation at high temperature where additionally high temperature gradients caused by the flame are present. The aluminium nitride ceramic plates are overshadowed with two additional plates, which serve as a thermal shield for the main heaters. Due to the significant mismatch in thermal expansion of alumina, aluminium nitride and quartz these components were not permanently bonded, but brought together with an elastic metal clump. The platinum resistors were made on the basis of ESL metallorganic composition D5051. Four layers printed with 260 mesh and separately fired at 950°C provide a sheet resistance of 1 Ohm per square. For the contact layers, a ESL 8880 gold conductive composition was applied. The leads were made with 0.3mm fine gold wires.

The ceramic sensor was attached to a brass base provided with gas fittings, and surrounded with a quartz tube, as shown in Fig. 8

Combustor temperature controller

The temperature of the combustor heaters is controlled by a synchronous pulsed modulator. The modulator is provided with suitable power heaters deposited on platinum substrates, power driving transistors and an additional voltage reference. The method of power compensation is the same as applied at the thermal flowmeter.
After each heat pulse, when the platinum resistors are disconnected from the power supply and are connected to the constant current source, the voltage drop across the platinum resistor is compared with a reference voltage. If the voltage across the platinum resistor is higher than the reference voltage in the following cycle, no power is provided to the platinum resistor. The modulator is timed with a repetition rate of 10 kilocycles, the width heat pulse equals 80μs and the aperture time for sampling the value of resistance equals 10μs. Because the temperature of platinum heaters is constant, the electrical power provided to the heaters is a linear function of the number of heat pulses delivered in an established time period.

3. Experimental

In Fig. 7 an experimental assembly is displayed.

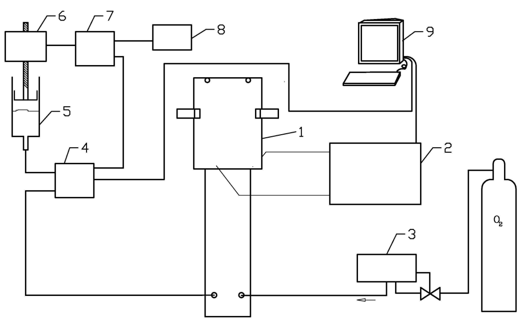

Fig. 7. Heat energy meter, 1- combustor, 2- temperature controller, 3-flowcontroller, 4- flowmeter with thermal sigma delta modulator, 5-syringe pump, 6 step motor, 7- frequency comparator and motor driver, 8- programmable oscillator, 9- computer.

It contains a combustor, syringe pump module, oxygen controller, computer and electronic circuits which interface the platinum heaters, and sensors. Fig. 8 displays the real experimental combustor mounted in the brass base surrounded by a glass shield.
The process of measurement involves the following steps:
- establishing the first value of fuel supply by selecting the first clock frequency,
- establishing the second value of fuel supply by selecting the second clock frequency,
- establishing the optimal value of oxygen supply.

Fig. 8 Real experimental combustor (centre) with flowmeter and syringe pump
(both on the left).

The optimal value of oxygen supply was established for the higher value of fuel supply. The value of oxygen supply was gradually increased and the electrical power delivered to the combustor was observed. The optimal value of fuel supply was selected for the minimum electric power delivered to the combustor.
The sensor was tested with gas fluid, (hydrogen) and liquid fluid (isopropylalcohol). For both the mentioned fluids, the measured combustion heat energy was approximately 90% of the specified lower heating value [11]. In Fig. 8, and Fig. 9, the recorded signals of fuel and electric power supply are displayed.

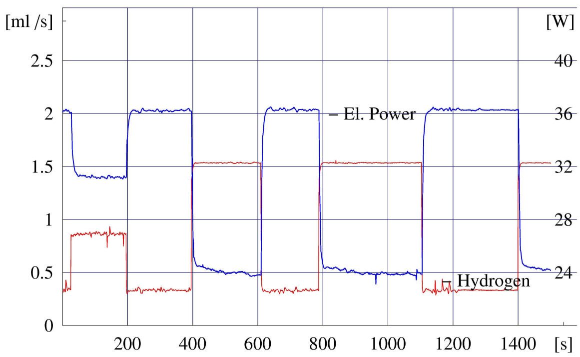

Fig. 9. Recorded signals for hydrogen supply and electric power supply.

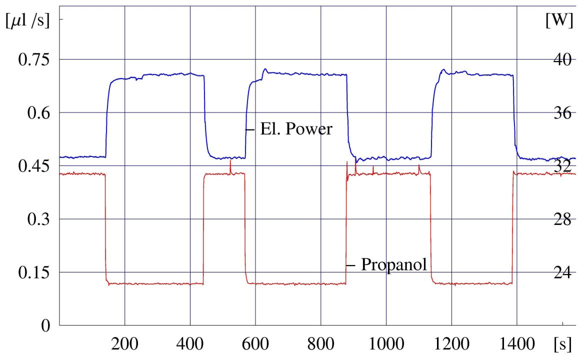

Fig. 10. Recorded signals for propanol supply and electric power supply.

4. Comments on accuracy

When carrying out the process of measurement, it is advantageous to set two levels of intensity for fuel supply and several times change the intensity of fuel supply. In this way, the offset errors produced by the flowmeter and electric power meter can be cancelled. Also, the influence of ambient temperature will be minimised. Assuming, that the ambient temperature between two cycles remains unchanged, the heat flux, which is spread out outside the combustor, also remains unchanged due to the constant temperature of the combustor.

Despite precision temperature compensation, there is a mismatch in density between the heat flux provided from a small flame and the compensating heat flux generated by the electric heaters. This fact produces significant changes in temperature gradients within the combustor ceramic structure, which finally has an influence on sensor response to fuel supply changes. For tracing the temperature in the vicinity of the combustion zone additional temperature supervising sensors may be applied.

This type of sensor measures the lower heating value (LHV), which is determined by subtracting the heat of vaporisation of the water from the higher heating value (HHV). The table displays the measured heat values for two fluid fuels.

Fuel	Heat energy [MJ/kg]		ratio [%]
	measured	LHV(HHV)	meas./LHV
hydrogen	106	121 (140)	88
propanol	28,6	30,7 (35)	93

The measurements completed with hydrogen and propanol show that the sensor recognises 88% and 93% respectively, of the value specified as the lower heating value (LHV). This discrepancy, in most parts, is attributed to the heat transferred by the stream of hot gases which are released from the combustor. This additional heat power can be roughly estimated as:

$$\Delta P=(\rho_O*\upsilon_O*c_O + \rho_F*\upsilon_F*c_F)*(T_H-T_L) \qquad (6)$$

where:

ρ_O , ρ_F - stands for density of oxygen and fuel respectively,

υ_O , υ_F - stands for flow intensity of oxygen and fuel respectively,

c_O, c_F - stands for specific heat of oxygen and fuel respectively,

T_H - stands for temperature of exhausted burning products at high fuel supply intensity,

T_L - stands for temperature of exhausted burning products at low fuel supply intensity.

Because the flow intensities of fuel and oxidant are known, in order to make the correction, additionally, only the measurement of exhaust gas temperature must be completed. This measurement can be done with a low thermal capacity thermocouple suspended just above the combustion chamber, and in this way, a more accurate heat energy meter can be accomplished.

5. Summary

- the proposed instrument enables direct measurement of the heating value of fluid fuels,
- the sensor recognises more than 85% of the factual calorific value of heat energy,
- the sensor shows good stability and reliability,

- platinum heaters deposited on high thermal conductivity ALN substrates, and provided with gold connectors are essential for accurate performance.

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