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DIGITAL MODERNIZATION OF A TEST STAND FOR THERMAL AND THRUST TESTING OF LIQUID ROCKET ENGINES

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Abstract. *This article presents the results of the digital modernization of a test stand for thermal and thrust testing of a low-thrust liquid rocket engine using gaseous O_2/CH_4 propellants. The aim of the article is to introduce the metrologically correct system, created during the research, for direct measurement of thrust, pressure, temperature, mass flow rates and subsequent recovery of derived parameters (characteristic velocity, heat flux, Mach numbers, etc.). The architecture of a measurement complex based on the National Instruments (NI) platform is proposed, the choice of primary transducers (strain gauge load cells, Kulite pressure transducers, Nanmac thermocouples, Bronkhorst flow meters) is justified considering the extreme operating conditions. The methodology for indirect estimation of heat flux based on a one-dimensional heat conduction model, implemented in the MATLAB environment, as well as the creation of a virtual monitoring interface in LabVIEW, are separately considered. The article provides a basis for conducting safe and accurate bench tests of advanced rocket engines using eco-friendly fuel*

Key words: *Liquid rocket engine, Test stands, Propellant type (O_2/CH_4), Digital modernization.*

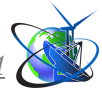
Introduction.

Modern trends in the development of rocket and space technology require the improvement of experimental research methods and the modernization of test infrastructure. Traditional test stands for liquid rocket engines (LREs) are often characterized by fragmented automation, the lack of a unified data acquisition system, and limited capabilities for analyzing the obtained results. The digital transformation of such stands allows for a significant increase in the accuracy, informativeness, and efficiency of testing.

The aim of the article is a basic description of the research on the comprehensive digital modernization of a test stand for thermal and thrust testing of a low-thrust LRE operating on gaseous O_2/CH_4 components. The main objective of such modernization is to create a unified digital environment for experiment control, data acquisition, analysis, and visualization.[1],[3]

The methodology is based on two key principles:

Flush-mounting of sensors;



Heat flux inversion.

Measurement Hypotheses and Acceptance Criteria.

Using time series of wall temperature, obtained from thermocouples, to calculate heat flux density $q''(t)$ based on a one-dimensional heat conduction model in a semi-infinite body with constant effective material properties.

For each measurement channel, working hypotheses and clear acceptance criteria were formulated (Table 1), which formed the basis of the verification and validation protocols.

Parameter	Hypothesis	Acceptance Criterion
Heat flux, q	Inversion from flush-mounted thermocouples and a 1D model ensures mean absolute error $\pm 10\%$ in quasi-stationary runs	$MAE(q'') \leq 10\%$; coefficient of variation $CV \leq 7\%$
Chamber pressure, P_c	Difference between static and dynamic channels at the same point does not exceed $\pm 5\%$ at the plateau	$(P_{c,stat} - P_{c,dyn})/P_c \leq 5\%$
Thrust, F	The load cell channel after calibration ensures a system error within $\pm 3\%$ fs	$RMSE(F) \leq 3\%$ fs
Characteristic velocity, c	c calculated from measured P_c and \dot{m} agrees with reference values within $\pm 5\%$	$\Delta c/c \leq 5\%$

The proposed set of hypotheses not only formalizes the accuracy requirements but also creates a metrological framework for the entire cycle of experimental research. This is a direct result and advantage of digital modernization, which allows for the quantitative assessment and control of every stage of testing.

Test stand configuration and sensor placement.

Figure 1 shows the general schematic of the test stand for engines using gaseous propellants to visually demonstrate the exact placement locations of various sensors and transducers after the completion of the current research.








The schematic is enriched with an image showing the placement of sensors and transducers.

Sensor placement was chosen to ensure:

- continuous and reliable measurement of key characteristics;
- minimal impact on the fuel flow and combustion products;
- potential for future system expansion (e.g., adding cooling, telemetry, etc.).

According to the color coding:

-  Flow meters are intended for measuring the mass flow rates of oxygen (O_2) and methane (CH_4), i.e., they measure the amount of propellants entering the engine combustion chamber.
-  The strain gauge load cell is intended for measuring engine thrust. This is a sensor that converts mechanical force into a corresponding electrical signal.
-  The static pressure transducer measures the absolute (static) pressure in the combustion chamber and in the nozzle. Static pressure is one of the main parameters affecting engine efficiency and operational stability.
-  The dynamic pressure transducer measures rapid pressure changes inside the combustion chamber. This is an important parameter for analyzing oscillations, combustion stability, and ensuring safe engine operation.
-  Thermocouples are installed in the walls of the combustion chamber and in the nozzle throat. These sensors allow for measuring the temperature of the engine's internal walls and assessing heat exchange processes, which are important for ensuring safety and the thermal resistance of the engine construction materials.[2],[4]

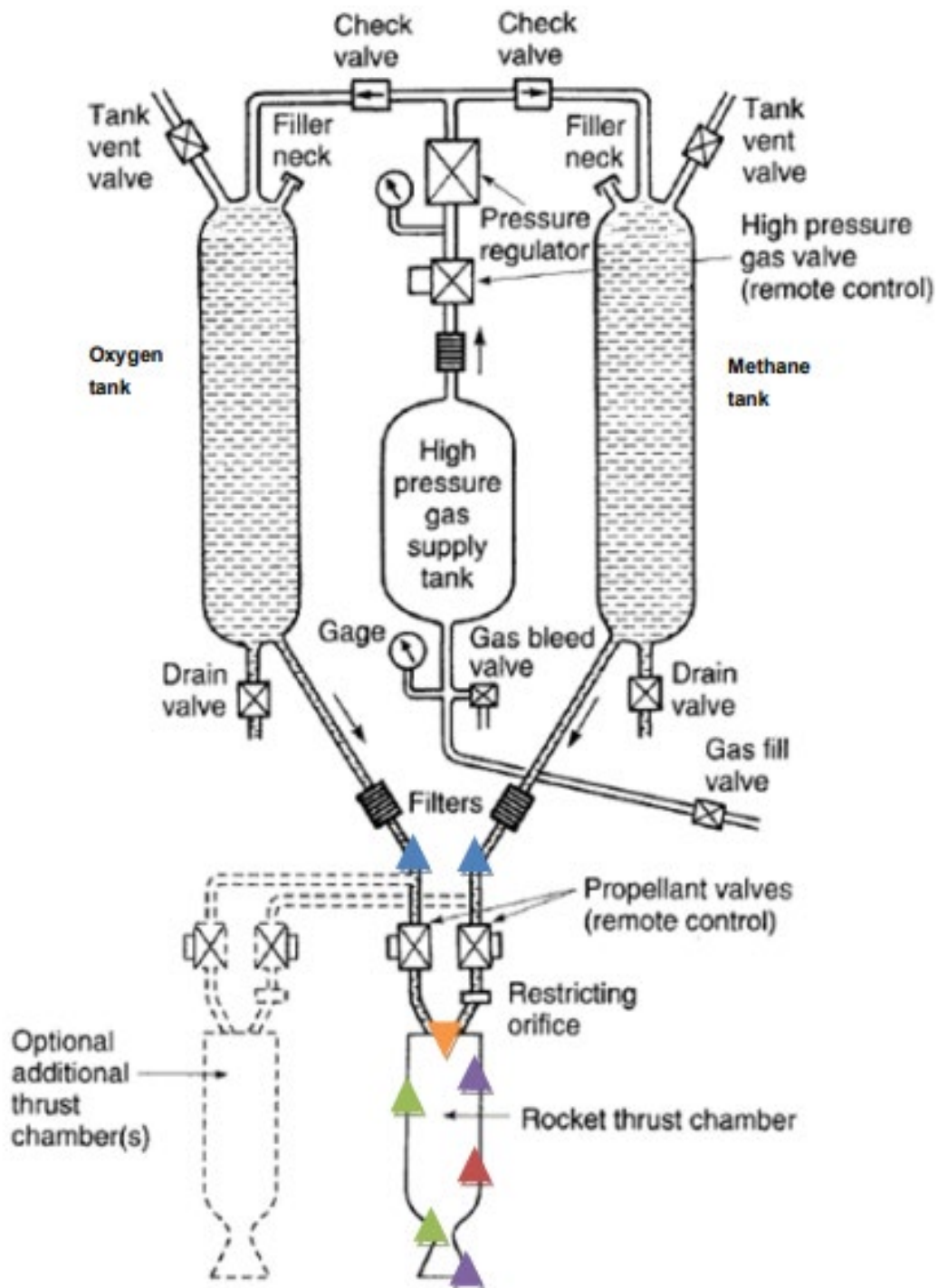
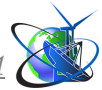


Figure 1 – General schematic of the test stand for engines using gaseous propellants [2].

Selection and integration of primary transducers.

For thrust measurement up to 500 N, the Honeywell Model 75 strain gauge load cell was selected with a rated load of 1110 N, providing a 200% safety margin. The sensor is a half-bridge type and requires bridge completion, filtering, and excitation.



All these functions are integrated into the NI-9237 data acquisition module.[6]

For measuring static and dynamic pressure in the combustion chamber (up to 100 bar) and static pressure at the nozzle exit (~1 bar), Kulite WCT-312 pressure transducers were selected. These sensors have a full Wheatstone bridge, are designed to operate under high-temperature conditions (up to 900 K), and are equipped with water cooling. Their signals are also processed by the NI-9237 module.[5]

For measuring the temperature of the inner wall of the combustion chamber (up to 900 K) and the nozzle throat (up to 800 K), high-temperature type K Nanmac E6-10 thermocouples were selected, with a diameter of 0.5 mm, in a compatible alloy sheath. A key feature is their flush mounting with a radial separation of 180° to increase measurement reliability and symmetry (Figure 2).

For processing their signals, including cold junction compensation (CJC), the NI-9219 module is used. [8]

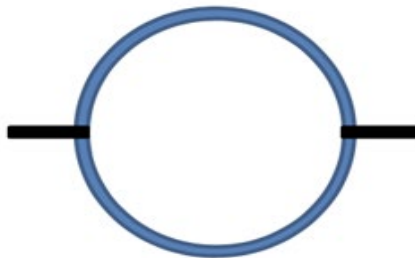


Figure 2 – Schematic of thermocouple placement with flush mounting and 180° diametral offset

The thermocouples are installed flush with the inner surface of the chamber wall to measure its temperature, which is significantly lower than the gas flow temperature due to the presence of the boundary layer and intensive heat removal. To prevent distortion of the heat flux and reduction in measurement accuracy due to the thermal bridging effect, a number of critical requirements were adhered to during their installation:

- The thermocouple design was chosen considering thermal compatibility with the wall material: a metal sheath made of nickel alloy (possible modification of the housing for a compatible material) and a ceramic filler ensure minimal temperature



gradients, so the thermocouple effectively indicates its own temperature, which equals the wall temperature;

– To avoid the effect of heat dissipation by the sensor itself, the thermocouple was press-fitted into a drilled hole, ensuring the necessary tight thermal contact.

The operating range of the thermocouples (up to 1100 °C) fully corresponds to the calculated wall and nozzle throat temperatures. Both sensors are manufactured by Nanmac Corporation, model E6-10 [7].

For measuring the mass flow rates of CH₄ (0.0622 kg/s) and O₂ (0.1244 kg/s) in the gas phase, Bronkhorst EL-FLOW thermal mass flow meters were selected. Their response time (≈500 ms) dictates the low required sampling frequency. The signal is processed by the NI-9219 module, and power is provided by an external PROMAX FA-665 source.

Data acquisition system architecture.

The digital modernization of the test stand primarily involves the creation of an integrated hardware-software platform capable of integrating diverse measurement channels. The hardware part of the data acquisition system is built on the National Instruments cDAQ platform. Below is the complete equipment schematic, verification of the analog-to-digital converter (ADC) resolution, and the recommended sampling frequency (Figure 3).

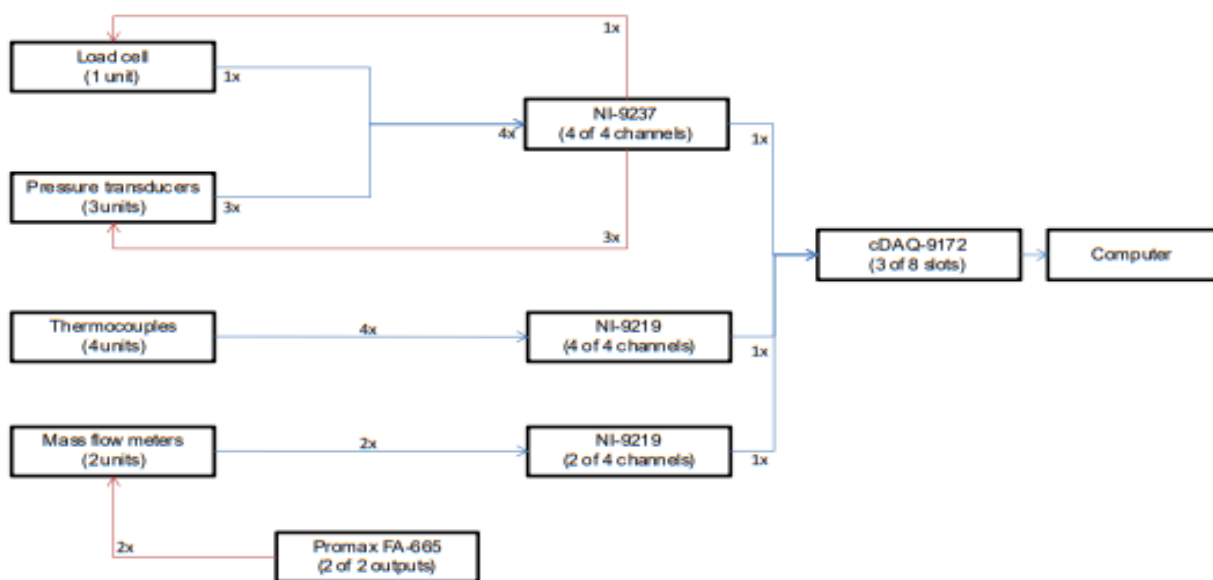
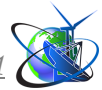


Figure 3 – General structure of the LRE instrumentation equipment



The selected commercial hardware complex meets the specifications for both signal conditioning and digitization. The ADCs, manufactured by National Instruments, connect to the cDAQ-9172 chassis (from the same manufacturer), guaranteeing compatibility with the LabVIEW environment.

It should be noted that the NI-9237 is specifically designed for processing signals from strain gauges and pressure transducers, so bridge completion is already built-in and does not require external implementation.

Furthermore, this module provides signal filtering, galvanic isolation, and excitation (i.e., sensor power).

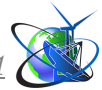
The hardware core consists of the National Instruments cDAQ-9172 modular data acquisition system with specialized modules:

- NI-9237 – for measuring thrust and pressure;
- NI-9219 – for measuring temperature and fuel flow.

For clarity and better understanding, the aforementioned specifications are presented in Table 1.

Table 1 – Digital signal processing functions

Type of Signal	Characteristic
Amplification	Not required – NI-9237 accepts signals up to ± 250 mV
Attenuation	Not applied
Isolation	Implemented in NI-9237
Filtering	Implemented in NI-9237
Excitation	10 VDC required – provided by NI-9237
Linearization	Outside the scope of the current research
Cold Junction Compensation	Not applicable to strain gauges
Bridge Completion	Required – implemented in NI-9237; Honeywell Model 75 sensor – half-bridge.



The metrological characteristics of the data acquisition system ensure high accuracy (Table 2). The resolution of the 24-bit ADCs is sufficient to record minimal signal changes from all sensors.

Table 2 – Analog-to-digital converter resolution

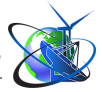
Transducer	Sensor Resolution	ADC Resolution (mV)
Strain Gauge	Infinitesimal	$2,980 \cdot 10^{-5}$
Pressure Transducer	Infinitesimal	$2,980 \cdot 10^{-5}$
Thermocouple	Infinitesimal	$1,490 \cdot 10^{-5}$
Flow Meter	Infinitesimal	$4,770 \cdot 10^{-4}$

Sampling frequencies were chosen considering process dynamics and sensor response times (Table 3), which avoids aliasing effects in accordance with the Nyquist theorem.

Table 3 – Proposed sampling frequencies

Measured Quantity	Frequency (samples/sec)
Thrust	2.5 kHz
Pressures	10 kHz
Temperatures	50 Hz
Mass Flow Rates	2 Hz

The measurement system provides a high level of accuracy for the main engine operating regimes; however, it has limited dynamic characteristics for temperature (determined by the thermal inertia of the thermocouple installation), which does not allow for the investigation of rapid thermal transients. It is worth noting that the 2 Hz frequency for flow meters is explained by the low signal dynamics and the actual physical limitations of the sensors. The final sampling frequency for each channel will be clarified after actual rocket testing, when the actual rate of change for each physical quantity becomes known.



Heat flux estimation methodology.

One of the key tasks was assessing the thermal load on the combustion chamber and nozzle walls. Due to the impossibility of direct gas temperature measurement (~ 3100 K), the heat flux inversion methodology based on wall temperature measurements from flush-mounted thermocouples was applied.

The used model is based on the solution of the non-stationary heat conduction problem for a semi-infinite body with constant properties. The heat flux density $q(t_n)$ at time t_n is calculated by the formula:

$$q(t_n) \approx \frac{2k}{\sqrt{\pi\alpha}} \sum_{i=1}^n m_i \left[(t_n - t_{i-1})^{\frac{1}{2}} - (t_n - t_i)^{\frac{1}{2}} \right]$$

where:

$q(t_n)$ – heat flux density at time t_n ,

k – thermal conductivity,

α – thermal diffusivity,

m_i – slope of the temperature graph on the interval $[t_{i-1}, t_i]$.

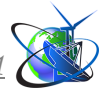
Since real data has a complex (higher-order) polynomial character, a piecewise linear approximation with a 'better' estimate of the derivative on each small interval is proposed; this procedure is formalized in the following formula and is the methodological basis of the inversion research:

$$m_i = \frac{\Delta T_i}{\Delta t_i}$$

Within this model, the values for k and α for the actual chamber/nozzle material are used as effective constants within the temperature range of the regime plateau.

From the functional considerations of the stand operation, the nozzle throat area is singled out separately, where the thermal load is expected to be the highest, and temperature signals may contain additional transients (e.g., due to flow separation).

This is why it is proposed to concentrate the sensors in one longitudinal plane in the nozzle area (with 180° radial separation) and apply the same inversion method described above. Additionally, the typical two-hump structure of launch records is noted: the primary peak from the momentary nozzle blocking and the second one from



the normal chamber pressure rise.

A key aspect of the modernization was the automation of thermal research. For calculation automation, an algorithm was developed in the MATLAB environment (Figure 4), which implements a piecewise linear approximation of the temperature derivative and forms an auxiliary matrix for calculating heat flux density.

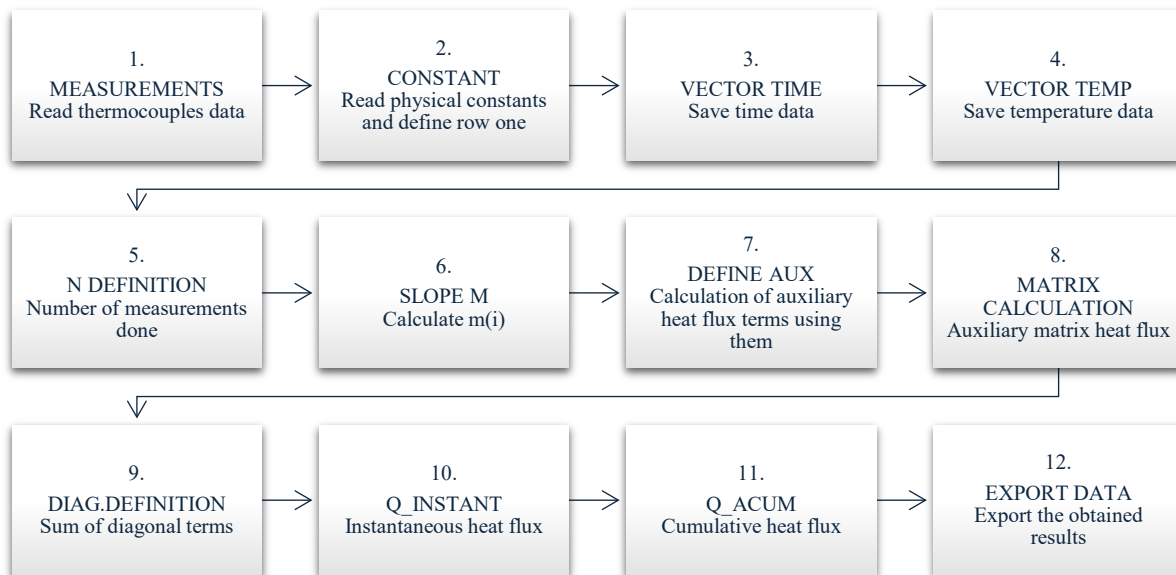


Figure 4 – Algorithm of the software tool for heat transfer calculation in MATLAB

For convenient visualization and experiment control, a virtual panel was developed in the LabVIEW environment (Figure 5).

The interface displays in real time:

- direct measurements: thrust, fuel flow rates, chamber pressure, temperatures;
- derived parameters: characteristic velocity c , exhaust velocity, Mach number, specific impulse;
- graphs of key parameter dependencies over time;
- safety light indicators (normal/emergency).

In other words, this is a demonstration of the block diagram in the LabVIEW environment, which is responsible for executing the test stand simulation and data acquisition algorithm.

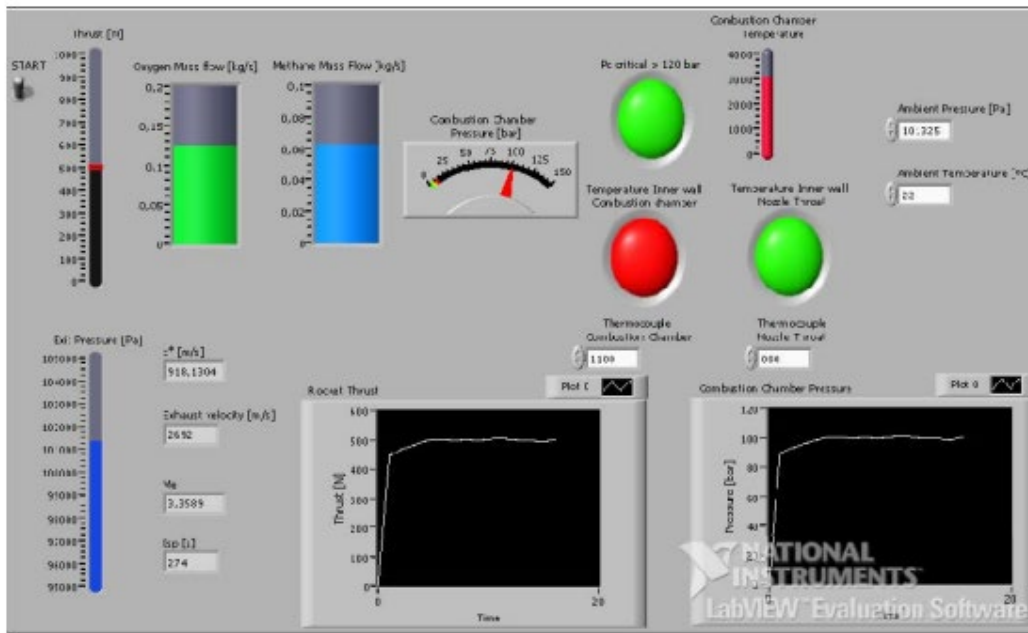
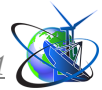


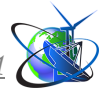
Figure 5 – Graphical user interface for monitoring test stand parameters in the LabVIEW environment

Results and discussion.

Since actual engine tests were not conducted, the methodology's effectiveness was verified through simulation. Test data for wall temperature were generated (Table 3), which were then processed in MATLAB.

Table 3 – Thermocouple saved data

t (s)	T (F)	T (C)
0	-10	-23
0,2	1390	754
0,4	1626	886
0,6	1783	973
0,8	1881	1027
1	1942	1061
1,2	1992	1089
1,4	2010	1099
1,6	2041	1116
1,8	2060	1127

**Table 3 – Thermocouple saved data (continued)**

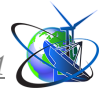
t (s)	T (F)	T (C)
2	2117	1158
2,2	2142	1172
2,4	2154	1179
2,6	2142	1172
2,8	2098	1148
3	2029	1109
3,2	1917	1047
3,4	1832	1000
3,6	1754	959
3,8	1620	899
4	1543	839

For complex computations, program code was developed in MATLAB. The code reads data from an Excel file (where thermocouple measurements are stored) and calculates instantaneous and accumulated heat flux.

The results of the instantaneous and accumulated heat flux calculation are presented in Table 4. The obtained values demonstrate physically correct behavior: a sharp heat flux peak at the beginning of the process followed by a decrease as the wall heats up.

Table 4 – Obtained results

Time	Instantaneous Heat [cal/cm² s]	Instantaneous Heat [W/m²]	Cumulative Heat [cal/cm²]	Cumulative Heat [J/m²]
1	190,2465	$4,54 \cdot 10^5$	265,28683	$6,34 \cdot 10^5$
1,2	175,508	$4,19 \cdot 10^5$	301,86228	$7,21 \cdot 10^5$
1,4	155,8172	$3,72 \cdot 10^5$	334,99479	$8,00 \cdot 10^5$
1,6	149,831	$3,58 \cdot 10^5$	365,55961	$8,73 \cdot 10^5$

**Table 4 – Obtained results (continued)**

Time	Instantaneous Heat [cal/cm ² s]	Instantaneous Heat [W/m ²]	Cumulative Heat [cal/cm ²]	Cumulative Heat [J/m ²]
1,8	139,7129	$3,34 \cdot 10^5$	394,514	$9,42 \cdot 10^5$
2	146,5383	$3,50 \cdot 10^5$	349933,4298	$1,01 \cdot 10^6$
2,2	135,7593	$3,24 \cdot 10^5$	324193,1325	$1,08 \cdot 10^6$
2,4	126,6151	$3,02 \cdot 10^5$	302356,8513	$1,14 \cdot 10^6$
2,6	112,8423	$2,69 \cdot 10^5$	269467,5085	$1,20 \cdot 10^6$
2,8	93,9024	$2,24 \cdot 10^5$	224238,9562	$1,25 \cdot 10^6$
3	74,2841	$1,77 \cdot 10^5$	177390,4285	$1,29 \cdot 10^6$
3,2	46,7727	$1,12 \cdot 10^5$	111693,3174	$1,32 \cdot 10^6$
3,4	39,5292	$9,44 \cdot 10^4$	94395,8144	$1,34 \cdot 10^6$
3,6	33,6965	$8,05 \cdot 10^4$	80467,3004	$1,35 \cdot 10^6$
3,8	13,6246	$3,25 \cdot 10^4$	32535,5261	$1,37 \cdot 10^6$
4	1,9347	$4,62 \cdot 10^3$	4619,9849	$1,37 \cdot 10^6$

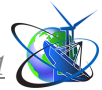
The logic of the LabVIEW virtual panel was also successfully tested on simulated data, confirming the correctness of the implemented algorithms for calculating derived parameters.

Conclusions.

During the research, a comprehensive methodology for experimental studies of a low-thrust liquid rocket engine using gaseous O₂/CH₄ was developed and systematized. The obtained results allow for the following conclusions:

➤ A complete measurement system was created: The proposed architecture based on National Instruments hardware (cDAQ-9172, NI-9237, NI-9219) ensures a full cycle of signal processing from various primary transducers (thrust, pressure, temperature, flow rate) with high accuracy.

➤ Sensor selection was justified: Specific transducer models (Honeywell, Kulite, Nanmac, Bronkhorst) were selected, meeting the requirements for ranges, accuracy,



and stability under the extreme conditions of a rocket engine.

➤ A thermal load assessment algorithm was developed: The heat flux inversion methodology implemented in MATLAB, based on data from flush-mounted thermocouples, allows for highly reliable estimation of the thermal load on critical engine components (combustion chamber, nozzle throat).

➤ A monitoring and analysis tool was developed: The created virtual interface in LabVIEW integrates all measurement channels, provides clear real-time data visualization, and automates the calculation of key engine performance characteristics.

➤ The methodology is prepared for implementation: Even within the framework of simulation modeling, the proposed approach proved its effectiveness. The established acceptance criteria and approaches to uncertainty budget assessment provide a basis for conducting correct, reproducible full-scale tests.

The developed system is technologically modern, metrologically sound, and constitutes a solid foundation for future experimental research on advanced rocket engines using eco-friendly fuel.

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