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Research Article

A modern data measurement system to study and test thermionic heat to electricity converters*

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Abstract

Studies and tests are conducted to determine the performance of thermionic nuclear power plants (TNPP) a stage in which is pre-irradiation testing of laboratory thermionic converters (TIC) with flat and cylindrically shaped electrodes using test facilities fitted with automated data measurement systems (DMS). The TIC volt-ampere characteristics (VAC) are measured in the DMS jointly with the measured test section and experimental test facility temperature fields. The structure and the characteristics of a DMS based on products from ICP DAS Co., Ltd are presented. A developed VAC measurement program providing the operator with a convenient graphic interface and enabling adjustment of the measurement parameters has been considered. The VAC recording errors in the process of measurements have been determined using TIC simulators. The error in the VAC diffusion portion on a simulator (with a current of less than 3 A) is not more than 1%. Thanks to the use of modern components, the developed DMS offers extended functional capabilities for measuring the thermocouple signals in an experimental electrophysical test facility. The DMS structure provides for the convenience of scaling (through a larger number of measuring channels) and makes it possible to add modules from other manufacturers. The experience of operating this DMS will be used to develop the DMS for an in-pile test system designed for similar functions.

Keywords

Thermionic converter, data measurement system, volt-ampere characteristic, thermocouples, pulse mode

Introduction

The TNPP has been one of the most advanced power sources for space vehicles for various applications (Yarygin 2013, Kuznetsov 1977). R&D activities have been under way in the recent decade to develop ground thermionic power plants with nuclear and gas-plasma heating (Yarygin et al. 2016). To determine the TNPP characteristics with computational (Polous et al. 2012) and experimental optimization of the thermionic process characteristics and "internal" parameters (Yarygin 2006), studies and tests are conducted a stage in which is pre-irradiation testing of laboratory TICs with flat and cylindrically shaped electrodes based on electrophysical test facilities. Different TIC modes and operating conditions of the thermionic fuel cell (TFC) electrodes are modeled as part of pre-irradiation studies using different test sections with TICs and TFCs fitted with automated DMSs (Andriashin et al. 1996, Yarygin et al. 2012).

The DMS is used for measurements of the TIC/TFC VAC together with measurements of the experimental test section and test facility temperature fields (Sinyavs-

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kiy 2000). Sensor signals arrive at the inputs of the I/O devices connected to the computer (Denisenko 2009, Shiryaev 2009). After being preprocessed, the measurement data is displayed in real time in the computer screen and is recorded to be further processed and entered in the databases used to calculate the TNPP thermionic fuel element (TFE) characteristics (Vinogradov et al. 2000, Vinogradov et al. 2001).

The TIC/TFC VAC, the dependence of the electrical current density *j* on the current voltage *U*, is of a complex nonlinear nature and is a function of the following six key parameters (Pyatnitskiy et al. 1967):

– emitter temperature T_E;
– collector temperature T_C;
– emitter electron work function Φ_E;
– collector electron work function Φ_C;
– cesium vapor pressure P_{Cs} (cesium tank temperature T_{Cs});
– interelectrode gap width (EGW) *d*.

Normally, in the process of one experimental measurement series, five of these parameters are kept constant and one parameter is variable. This results in one VAC family. The set of the VAC families measured by pulse method with different T_E, T_C, P_{Cs} (T_{Cs}) and *d* values is a part of the VAC atlas which is the initial one for determining the internal TIC/TFC parameters.

Measurement technique

A DMS makes it possible to measure the VAC both in a static mode (isopower VACs) and in a pulse mode (isothermal VACs). It provides extra diagnostic capabilities for determining the TIC/TFC internal parameters using representative VAC points (Yarygin 2006). The electrode temperature variation in the pulse mode shall not exceed four degrees. A dedicated TIC current control algorithm has been developed to fulfill this condition.

Two DMS versions have been developed (DMS-75 and DMS-600) which, depending on the working area of the tested TIC/TFC electrodes, use power devices with the maximum pulse current (respectively 75 and 600 A) for the current control, each of which consists of a computer-controlled high-capacity push-pull emitter follower assembled using parallel-connected bipolar transistors of the KT819 type. The TIC/TFC is connected as the emitter follower load. The power device is controlled from a digital-analog converter (DAC) of the PCI-1602F board from ICP DAS Co., Ltd (a well-known manufacturer of data acquisition and control system equipment) (ICP DAS websit 2017, Grafkin and Ioffe 2009) installed in the PCI slot of the computer's mother board (with an operational system not worse than Windows XP) (Fig. 1).

The control voltage generated by the VAC_Temp VAC measurement program has a saw-tooth stepped shape (Fig. 2) (Andriashin et al. 1996). The current *I* and the voltage *U* from, respectively, the shunt (the precision resistance with two outputs for the connection to the circuit and two inputs for removing the voltage proportional to the circuit-measured current) (Kolpakov 2010) and from the TIC/TFC potentiometric terminals are measured at each step using analog-digital converters (ADC) of the PCI-1602F board. The control voltage parameters (the number and the duration of the steps) can be varied by the operator in a broad range. The step duration is not more than 1 ms, and the total number of the VAC points is not less than 200.

The PCI-1602F performance is given in Table 1 (ICP DAS websit 2017).

A number of shunts (accuracy class 0.2) designed for different current ranges are used in the DMS. In the process of measurements, the DMS operator uses the handheld control panel to switch the current polarity to measure the forward-bias (emitter) or reverse-bias (collector) VAC region and to connect one of the shunts for obtaining the maximum sensitivity of the measuring channel in the selected current measurement range.

The rated-current shunt voltage drop is 75 mV, as the rated current is permitted to be not less than 300% higher in the pulse mode. This makes it possible to increase greatly the ADC input voltage and to reduce, as a consequence, the measurement error.

Thermocouples of the chromel-alumel and tungsten-rhenium types are used for measuring the temperature in the DMS respectively at a temperature of 0 to 1000–1300 °C and 1300 to 2000 °C and higher (Arnoldov et al. 2012). The thermocouple readings are measured using dedicated thermocouple signal input modules of the I-7018 type from ICP DAS (see Fig. 1) which are intellectual measuring devices with the functional capabilities extended thanks to a built-in microprocessor (Rannev 2010) and have the following advantages:

– programmed compensation of the cold junction temperature;
– automatic conversion of the thermal emf value to the temperature value using a calibration chart or a polynomial;
– digital filtration of input signals;
– detection of the thermocouple communications line breaks;
– protection against the computer malfunctions by using a dual watchdog timer (ICP DAS websit 2017, Kirillov and Agafonov 2016).

The basic error of I-7018 is 0.1%. The DMS uses a number of I-7018 models networked for the transmission of signals from several dozen of thermocouples. The I-7018 modules communicate with the computer through the I-7520 interface converter and a serial COM port**.**

The developed VAC_Temp program provides the operator with a convenient graphic interface and enables adjustment of a large number of the VAC measurement parameters and thermocouple indications. The I-7018 modules and the PCI-1602F board are controlled using

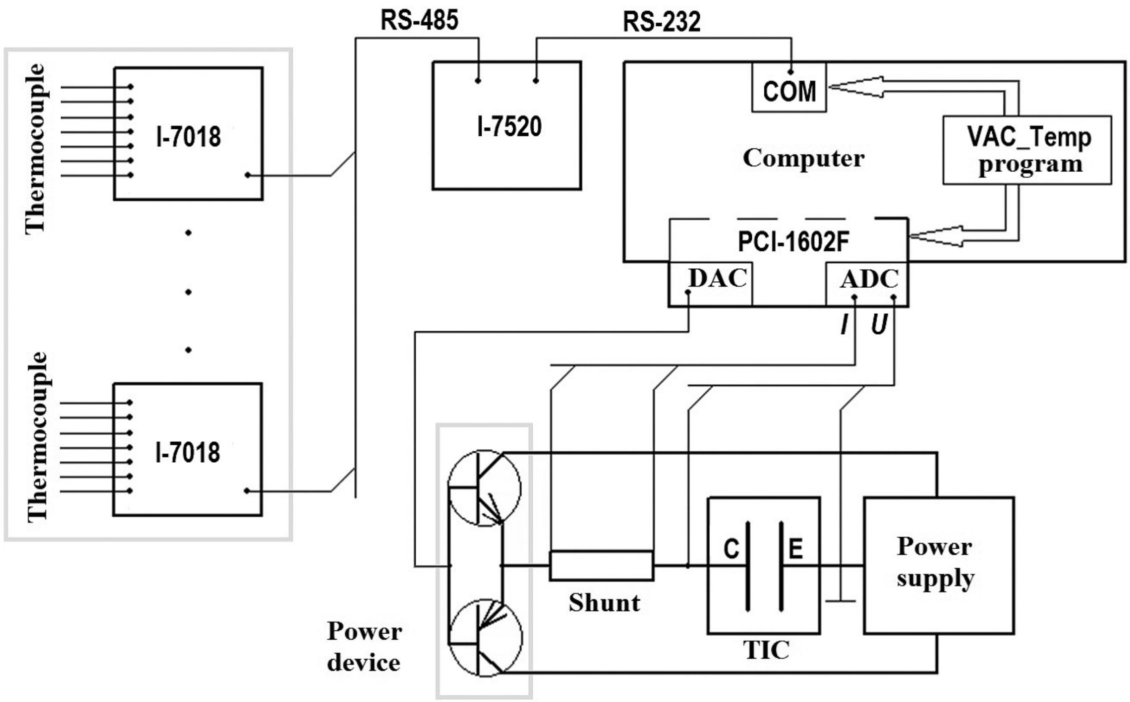

Figure 1. DMS block diagram.

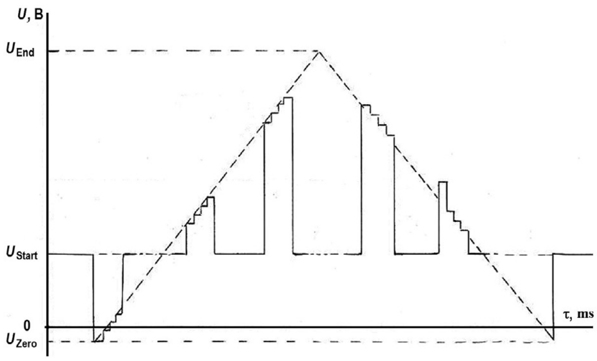

Figure 2. Shape of the VAC measurement control signal.

a set of drivers. The program's main window (Fig. 3) contains measurement data and the key parameters of the measuring process. The source code written in the C-language can be divided into the following parts:

– implementation of the VAC current control and measurement algorithm;
– thermocouple signal polling and conversion using calibration charts;
– generation of the graphic interface.

Determination of the VAC measurement error

Measurements were performed using the TIC emitters (standard resistors of the accuracy class 0.02) to determine the accuracy of the VAC measurement in DMS-75.

Table 1. PCI-1602F performance.

DAC capacity	12 bit
DAC output voltage range	±10 V; ±5 V
ADC capacity	16 bit
ADC input voltage range	±10 V; ±5 V; ±2.5 V; ±1.25 V
Number of differential channels in ADC	16
ADC maximum sampling rate	$2*10^5$ Hz

Table 2. Measuring shunt performance.

Shunt No.	R_{sh}, Ω	I_{rat}, A
1	0.0015	50
2	0.0075	10
3	0.1	0.75

The resistor ratings are $R_1 = 0.001$ Ω, $R_2 = 0.01$ Ω, $R_3 = 1$ Ω, and $R_4 = 100$ Ω.

Measurements were performed in the voltage range (U) of –10 to +10 V and the current range (I) of –20 to +70 A. Table 2 presents the resistances and the rated currents of the measuring shunts used in DMS-75.

Prior to the measurement, the measuring channels were calibrated using a standard digital voltmeter, Agilent 34401A (Agilent Technologies website 2017). Stepped-variable voltage was supplied in the process of calibration to the inputs of the PCI-1602F ADC and the standard voltmeter. The voltage was measured at each step using the voltmeter, and the readings were taken from the computer screen. As a result, dependences of the PCI-1602F readings on the standard instrument readings have been obtained and the calibration factors have been stored in the VAC measuring program.

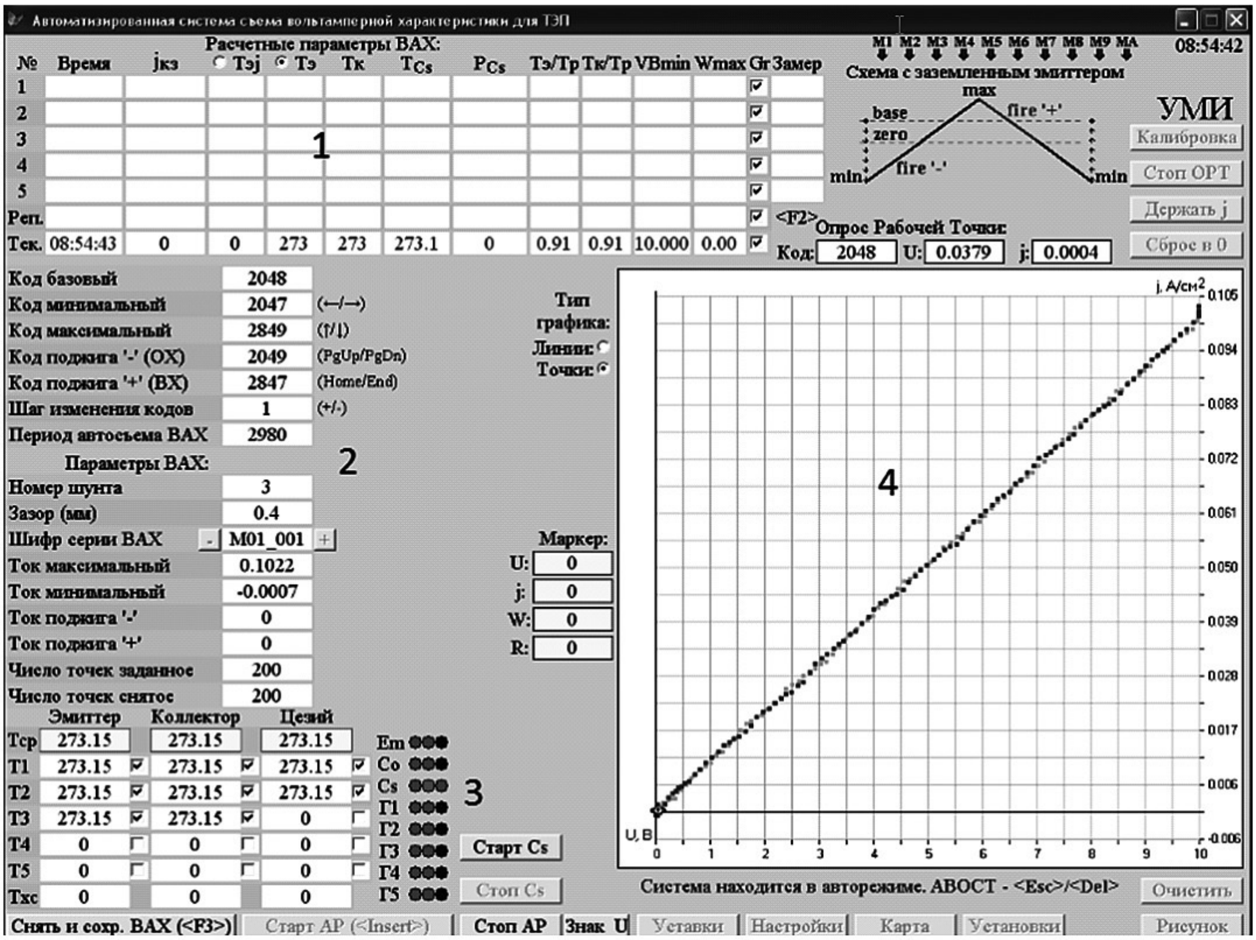

Figure 3. Main window of the VAC measurement program: 1 – parameters field of the latest recorded VACs; 2 – current control algorithm adjustment field; 3 – emitter, collector and cesium tank temperature measurement data field; 4 – VAC curve field.

Table 3. Resistance measurement errors.

Standard resistor R, Ω	Current polarity	Shunt	Current range, A		
			Error <d>, %		
			1–5	5–10	> 10
0.001	+	1	4.9	1.9	0.8
0.001	+	2	6.1	1.8	0.8
0.001	–	2	4.8	2.0	1.1
			0.2–1	1–5	> 5
0.01	+	1	10	2.3	0.9
0.01	+	2	3.5	1.0	0.9
0.01	–	2	3.8	1.3	1.0
			0.01–0.05	0.05–0.2	0.2–1
1	+	3	2.5	0.7	0.4
1	–	3	1.9	0.5	0.2
			0.01–0.02	0.02–0.05	0.05–0.1
100	+	3	3.3	1.3	0.7
100	–	3	2.6	1.4	0.8

The following algorithm was used to process the measurement results.

1. An array of the $I(U)$ data (the number of points in each current range is $N > 100$) was recorded for each combination of the standard resistor R, the current polarity and the measuring shunt.
2. Resistance was calculated for each point i $R_i = U_i / I_i$. (1)
3. The average relative resistance measurement error was computed in the selected current range

$$< \delta >= \frac{1}{N}\sum_{i=1}^{N} | R - R_i | / R. \quad (2)$$

Table 3 presents the error calculation results from which it follows that

– with $R > 0.001$ Ω, the error does not exceed 2% ($I >$ 10 A);
– with $R < 100$ Ω, the error does not exceed 1% ($I >$ 50 mA).

Conclusion

Thanks to using modern components, the developed DMS offers extended functional capabilities for measuring the thermocouple signals in an experimental electrophysical test facility. The error of the VAC diffusion portion pulse-mode measurement ($I < 3$ A) using a TIC simulator does not exceed 1%.

As compared with the earlier DMS developed based on the CAMAC modules (Andriashin et al. 1996), the new DMS version is compatible with the interfaces of modern computers, is fitted with native software for the module setting and trouble-shooting, and offers convenience of scaling (through a larger number of measuring channels) with a capability to add modules from other manufacturers.

The experience of operating this DMS will be used to develop the DMS for the in-pile test system designed for similar functions.

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