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FTD-ID(RS)T-1128-88

AD-A207 166

# FOREIGN TECHNOLOGY DIVISION

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by

A.B. Ambrazevicius, P. Yu. Valatkevicius, et al.

# HUMAN TRANSLATION

FTD-ID(RS)T-1128-88 7 April 1989

MICROFICHE NR: FTD-89-C-000234

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English pages: 18

Source: Trudy Akademii Nauk Litovskoy SSR,
Seriya B, Khimiya, Tekhnika, Fizicheskaya
Geografiya, Nr. 4(67), 1971, pp. 115-125

Country of origin: USSR
Translated by: Charles T. Ostertag, Jr.
Requester: AEDC/DOTI/Myra W. Price


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| Block | Italic | Transliteration | Block | Italic | Transliteration |
|---|---|---|---|---|---|
| А а | *А а* | A, a | Р р | *Р р* | R, r |
| Б б | *Б б* | B, b | С с | *С с* | S, s |
| В в | *В в* | V, v | Т т | *Т т* | T, t |
| Г г | *Г г* | G, g | У у | *У у* | U, u |
| Д д | *Д д* | D, d | Ф ф | *Ф ф* | F, f |
| Е е | *Е е* | Ye, ye; E, e* | Х х | *Х х* | Kh, kh |
| Ж ж | *Ж ж* | Zh, zh | Ц ц | *Ц ц* | Ts, ts |
| З з | *З з* | Z, z | Ч ч | *Ч ч* | Ch, ch |
| И и | *И и* | I, i | Ш ш | *Ш ш* | Sh, sh |
| Й й | *Й й* | Y, y | Щ щ | *Щ щ* | Shch, shch |
| К к | *К к* | K, k | Ъ ъ | *Ъ ъ* | " |
| Л л | *Л л* | L, l | Ы ы | *Ы ы* | Y, y |
| М м | *М м* | M, m | Ь ь | *Ь ь* | ' |
| Н н | *Н н* | N, n | Э э | *Э э* | E, e |
| О о | *О о* | O, o | Ю ю | *Ю ю* | Yu, yu |
| П п | *П п* | P, p | Я я | *Я я* | Ya, ya |

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.



## RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

| Russian | English | Russian | English | Russian | English |
|---|---|---|---|---|---|
| sin | sin | sh | sinh | arc sh | $\sinh^{-1}$ |
| cos | cos | ch | cosh | arc ch | $\cosh^{-1}$ |
| tg | tan | th | tanh | arc th | $\tanh^{-1}$ |
| ctg | cot | cth | coth | arc cth | $\coth^{-1}$ |
| sec | sec | sch | sech | arc sch | $\text{sech}^{-1}$ |
| cosec | csc | csch | csch | arc csch | $\text{csch}^{-1}$ |

| Russian | English |
|---|---|
| rot | curl |
| lg | log |

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# ELECTRICAL AND GAS-DYNAMIC CHARACTERISTICS OF AN ELECTRIC-ARC GAS HEATER

A.B. Ambrazevicius, P.Yu. Valatkevicius, R.M. Kezelis, and R.A. Juskevicius

Institute of Physico-technical Problems of Power Engineering
Academy of Sciences, Lithuanian SSR

Submitted 3 February 1971

[abstract] An investigation and generalization are made of the volt-ampere characteristics and thermal efficiency of a dc electric-arc heater in a vortex layout with a power of 300 kW with a mixing chamber and lateral discharge of the untwisted jet. The heater operates in the area of ascending volt-ampere characteristics. The installation which was developed was used for investigating processes of turbulent heat exchange and resistance in high-temperature flows of argon, nitrogen, and air. Maximum flow rate of gases - 60 g/s, range of mean-mass flow temperatures - 1000-5000$^{\circ}$K. The velocity and temperature (up to 3200$^{\circ}$K) profiles were measured with the help of a calorimetric probe at a distance l/d=18 from the entrance into a tube with d=20 mm.
10 illustrations, 17 references, abstracts in English and Lithuanian.

Russian translations.

An investigation was conducted and a generalization made of the volt-ampere characteristics (VAC) and thermal efficiency of a dc electric-arc heater with a power of 300 kW with a mixing chamber and lateral discharge of the untwisted jet.

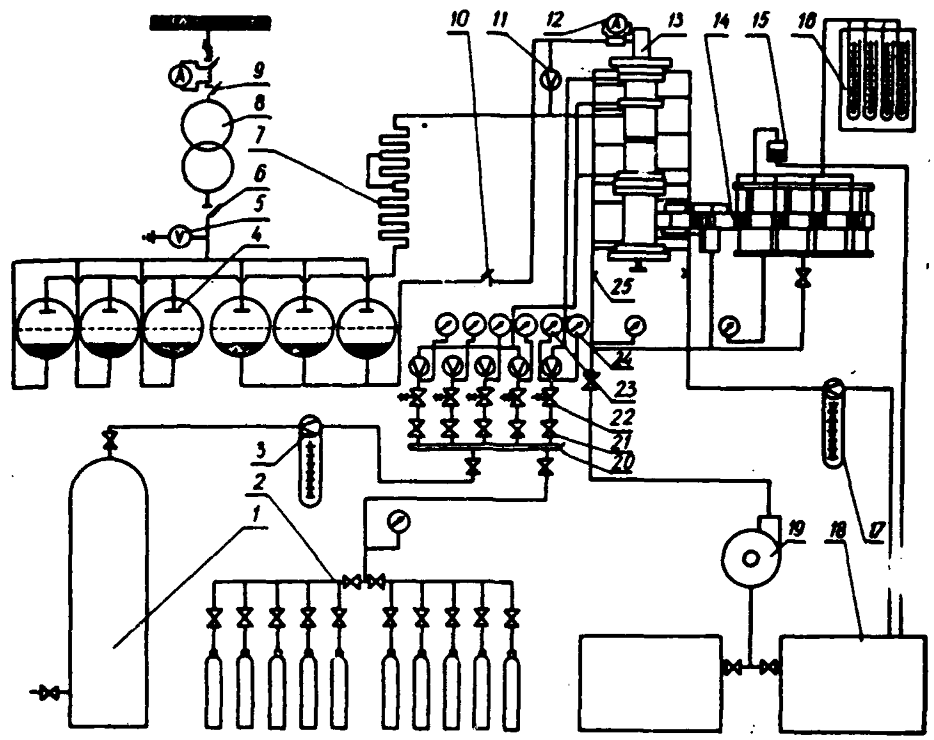

Figure 1. Layout of the experimental installation. 1 - air receiver, 2 - oxygen ramp, 3 - measuring diaphragm, 4 - rectifier RMV 250x6-III, 5 - voltmeter, 6 - contactor KTV-35, 7 - rheostat, 8 - transformer 0.4/0.6, 9 - automatic device, 10 - on-off switch VAB-20, 11 - voltmeter *M 106/1*, 12 - *ammeter* M 105, 13 - electric-arc heater, 14 - experimental section, 15 - measuring tank, 16 - bank of U-shaped manometers, 17 - measuring diaphragm, 18 - receptacles 2x10 $m^3$, 19 - pump ZMS-10, 20 - thermometer, 21 - regulating valves, 22 - valves with an electric drive, 23 - critical flow rate disks with standard pressure gages, 24 - contact manometer, 25 - differential thermocouple.

Investigation of processes of high-temperature heat exchange and the behavior of high-temperature materials is one of the most important specialties at the institute, therefore a great deal of attention was given to the creation of installations with high-temperature heating of gases. Along with other methods of heating the electric-arc method was used. It is used extensively at the present time in metallurgy, plasma chemistry, and other areas of new technology.

The high-temperature gas-dynamic installation (300 kW) which was used included: step-up transformer 0.4/0.6 kV with a power of 500 kW, an RMV 250x6-III mercury rectifier with a voltage of 750 V and current force of 750 A, a high-pressure 3Ms-10 pump, water receptacles with a capacity of 20 $m^3$, ramps for 40 gas cylinders, and a 40 atm air compressor with receiver (see Fig. 1).

On the whole all of this is necessary for power supply of an electric-arc heater (EDP). All control and measuring systems came out on a separate remote control panel.

The installation which was developed was used for investigating the processes of turbulent heat exchange and resistance in high-temperature flows of argon (Ar), nitrogen ($N_2$), and air. Maximum flow rate of gases ($G_r$) - 60 g/s, range of mean-mass flow temperatures ($T_f$) - 1000-5000°K. The velocity and temperature (up to 3200°K) profiles were measured with the help of a calorimetric probe at a distance l/d=18 from the entrance to the tube with d=20 mm.

## 1. Special features of construction of the EDP

A distinctive feature of the vortex-type EDP with central hot cathode which was used is the use of an interelectrode insert (MEV) and a multistage anode. This layout was developed at the ITPM SO AS USSR [1-7].

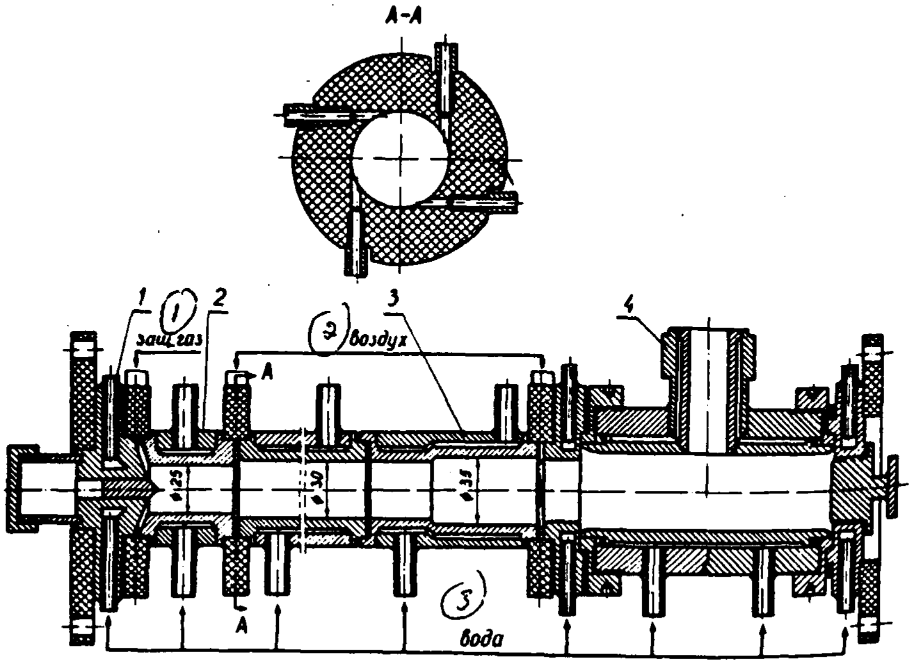


Figure 2. Vortex-type dc electric-arc heater. 1 - cathode; 2 - interelectrode insert; 3 - multistage anode; 4 - mixing chamber.

Key: (1) Protective gas; (2) Air; (3) Water.

Our EDP (Fig. 2) has an elongated MEV (d=25 mm, l/d=2), due to which it is simpler to come onto mode. For regulating the mean-mass temperature on the outlet from the mixing chamber a supply of cold gas was provided beyond the EDP. In all the isolation rings the gas was supplied tangentially for stabilizing the arc with the vortex and cutting down heat losses in the wall of the MEV and the anode. Since rotation of flow was not desirable a side discharge of the jet was provided.

A central hot cathode made out of lanthanated tungsten or zirconium with d=10 mm was used for fixing the length of the arc.

In order to avoid the rapid oxidation of tungsten in ring I of the twist which was made out of glass textolite a protective inert gas was supplied - ($N_2$ or Ar up to 2 g/s). If zirconium is used (up to a specific current strength) air can be supplied in place of the inert gas.

The end II of the arc was fixed thanks to the multistage construction of the anode [4, 8]. Diameter of the working section of the anode - 35 or 40 mm. Fixation of the arc was realized in the beginning of formation of the boundary layer on the working section of the anode, where the surface temperature is raised [4, 6]. In this place the conditions of breakdown are improved.

Fixing of arc length makes it possible to obtain ascending VAC up to a specific current strength. With an increase of current strength or lessening of the flow rate the arc is shunted in the section of the anode with a smaller diameter. In this case a conventional EDP with a smooth anode and falling VAC is obtained.

For assuring the stable operation of the EDP in such a mode and protecting the electric circuit from an excessive increase of current strength a ballast resistance was added. It consisted of a Nichrome water-cooled 0.7 ohm rheostat for the smooth readjustment of mode.

As is known, the introduction of the additional resistance cuts down the electrical efficiency of the installation considerably, and therefore from an economic point of view it is desirable to operate in modes of ascending VAC without ballast rheostats.

The arc was ignited by a wire which was introduced through a special shutoff window in the mixing chamber. Tests were made on ignition by means of short circuiting with the wire of the cathode with MEV, but in the case of short incendiary currents greater startup current strengths are obtained, thus lessening the service life of the cathode considerably.

The energy balance of the EDP was determined by measuring the drop of voltage (U), current strength (I), amount of gases ($G_r$), cooled water ($G_B$), and its temperature drop. The latter was measured with 4-junction copper-konstantan thermocouples. $G_r$ and $G_B$ were measured with diaphragms, $G_r$ was measured additionally with critical flow rate disks with standard pressure gages.

## 2. Energy characteristics of the EDP

As is evident from Figure 3, with an increase of I the ascending VAC becomes descending. The position of maximum of U with a lessening of $G_r$ is shifted to the side of lesser values of I. With large $G_r$ and I up to 300 A it is possible to operate without ballast resistance.

This is assured by the high electrical efficiency and minimum erosion of the electrodes.

The nature of the protective gas - Ar, $N_2$, or air - has a great influence on the VAC. As is evident from Figure 4, with the same value of it, ~2 g/s, and a working diameter of 35 mm for the anode, the VAC are very different.

For the calculation of other modes of operation of EDP on the basis of these curves the theory of similarity is used. Many authors have mentioned its use for EDP [8-13]. Data, generalized using such a method and obtained when working with $N_2$, Ar and air, fit satisfactorily on one curve, which may be described by the criterial *equation (Fig. 5)*

$$\frac{Ud\sigma_0}{I} = A\left(\frac{I^2}{\bar{G}_r d\sigma_0 H_0}\right)^n,$$

where: U - voltage drop on the EDP (b), I - current strength (A), d - diameter (cm), $G_r$ - flow rate of gas (g/s), $H_0$ - gas enthalpy (kJ/g), $\sigma_0$ - conductivity of gas (1 ohm·cm).

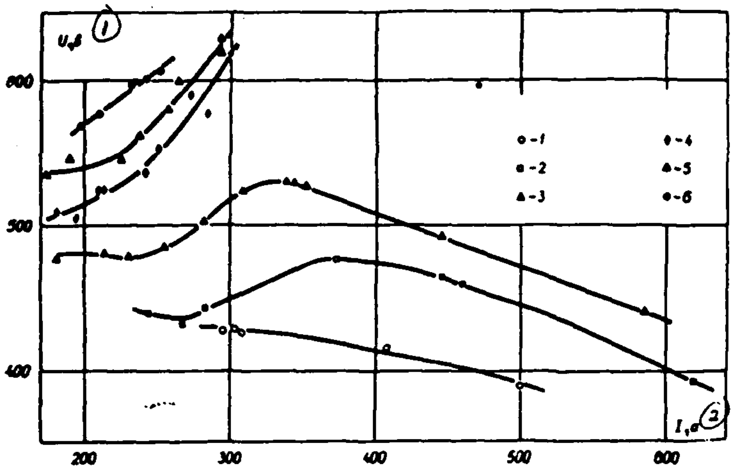


Figure 3. Volt-ampere characteristics of the arc at different flow rates of gas ($G_r$): 1 - 14, 2 - 17, 3 - 19, 4 - 25, 5 - 30, 6 - 35 g/s. Flow rate of protective gas ($G_r$) - 3 g/s. Working section of anode - 40 mm.
Key: (1) V; (2) A.

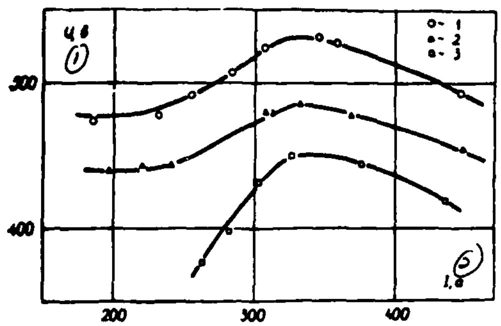


Figure 4. Volt-ampere characteristics of the arc depending on the kind of protective gas. $G_r$ - 19, $G_l$ - 2 g/s. 1 - protective gas - ($N_2$), 2 - without protective gas, 3 - protective gas - (Ar).
Key: (1) V; (2) A.

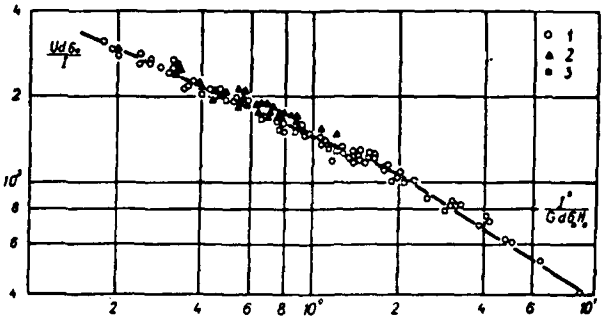


Figure 5. Generalized volt-ampere characteristics of the arc with different $G_r$. 1 - protective gas ($N_2$), 2 - without protective gas, 3 - protective gas (Ar).

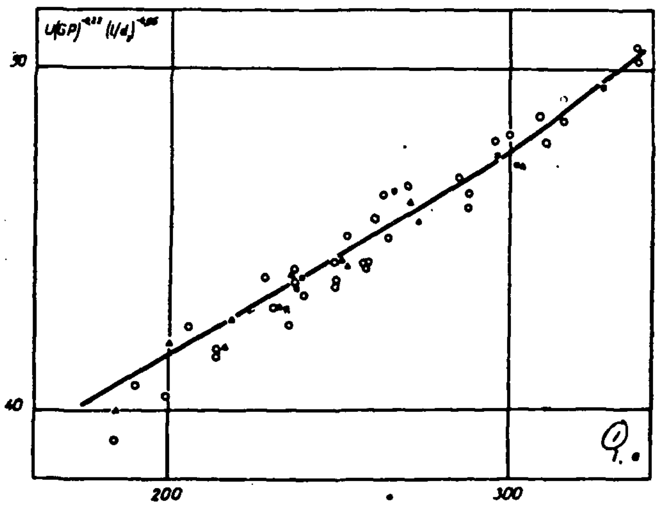


Figure 6. Ascending volt-ampere characteristics, generalized using the method proposed in [6].
Key: (1) A.

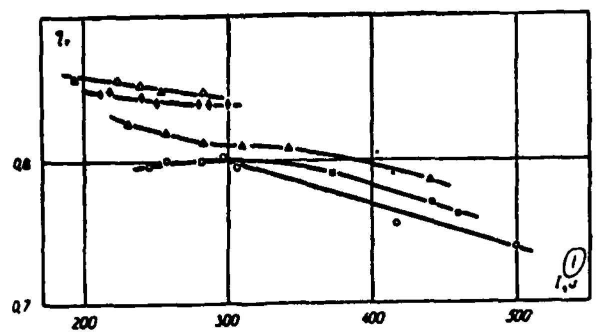

Figure 7. Efficiency of an EDP for different $G_{\Gamma}$. Designations the same as in Figure 3.
Key: (1) A.

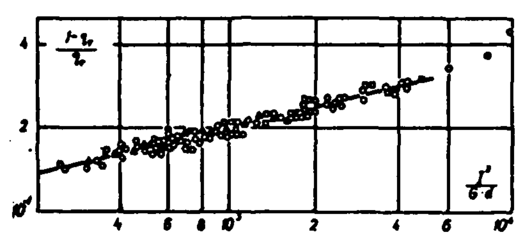

Figure 8. Generalized efficiency of an EDP with different $G_{\Gamma}$ and different $G_{I}$. Designations the same as in Figure 5.

The values of $\sigma_0$ and $H_0$ are taken from [13]. Values of $\sigma_0$ and $H_0$ for the mixture of gases consisting of 10% Ar or $N_2$ and 90% air were used for approximation I. Coefficients A and n depend on the construction of the heater, kind of gas, polarity, etc. For ascending branches A=145, n=-0.44, and for descending A=165, n=-0.63. The ascending branches of the characteristics were generalized using the method proposed in [3, 6] (Fig. 6). The result when $d_2/d_3=1.165$

$$U=27\left(1+6{,}5\cdot 10^{-3}\,\frac{I}{d_2}\right)\left(\frac{G_\Gamma}{d_2}\right)^{0{,}22}\left(\frac{I}{d_2}\right)^{0{,}95}(Pd_2)^{0{,}23},$$

where $d_2$ - in cm, P - in atm (1 atm accepted), $G_\Gamma$ - flow rate of gas (g/s).

The thermal efficiency is very important for calculations and an economic evaluation of an EDP. It takes into consideration the share of heat losses ($\eta_T$), outgoing with the cooling water, and determines the relative amount of energy, going out with the jet:

$$\eta_T=1-\frac{N_B}{N}=\frac{N_C}{N},$$

where N=IU - electric power (kW) supplied to the EDP, $N_C$ - power, entering the jet (kW), $N_B$ - heat losses with the cooling water (kW).

The designers endeavor to organize the supply of gas in such a manner as to protect the walls from the hot arc with a layer of cold gas. $\eta_T$ increases noticeably with an increase of $G_\Gamma$ and is lowered with an increase of I (Fig. 7). It is interesting to note that with a recalculation of $\eta_{\Gamma}$ in another form

$$\frac{1-\eta_T}{\eta_T} = \frac{N_{\text{в}}}{N_c} = \frac{4l}{d} St$$

a correlation is obtained for the amount of convective heat to the heat which is carried away by the flow, which for EDP of the same dimensions is directly proportional to the Stanton number [4]. Just as in the case with the VAC, the curves for thermal efficiency (Fig. 7) can be generalized. As a result a curve (Fig. 8) is obtained which corresponds to the equation

$$\frac{1-\eta_T}{\eta_T} = B\left(\frac{I^2}{G_\Gamma d_2}\right)^m,$$

where $G_\Gamma$ - in g/s, $d_2$ - in cm.

Using $N_2$ as the protective gas , and without using a protective gas (cathode made from zirconium) in approximation I we obtain B=0.038 and m=0.24.

In the case of low $G_\Gamma$ (14-17 g/s) and high I (500-650 A) the points deviate from the general curve. Evidently these deviations can be explained by laminarization of the flow. If $\eta_\Gamma$ is known it is possible to determine the power in the jet $N_c$ and in the case of $G_\Gamma$ being known - the mean-mass enthalpy $H_f$ and $T_f$. Based on known $T_f$, $G_\Gamma$ and a transverse section $F = \frac{\pi d^2}{4}$ it is possible to calculate the mean-mass velocity ($w$).

3. Gas-dynamic characteristics of the EDP

For checking the average variables mentioned above and determining the nature of the stream it is necessary to make measurements of the fields of velocities and temperatures (T). For this purpose we used a Pitot tube and a calorimetric probe [14, 15], the basic layout of which is shown in Figure 9.

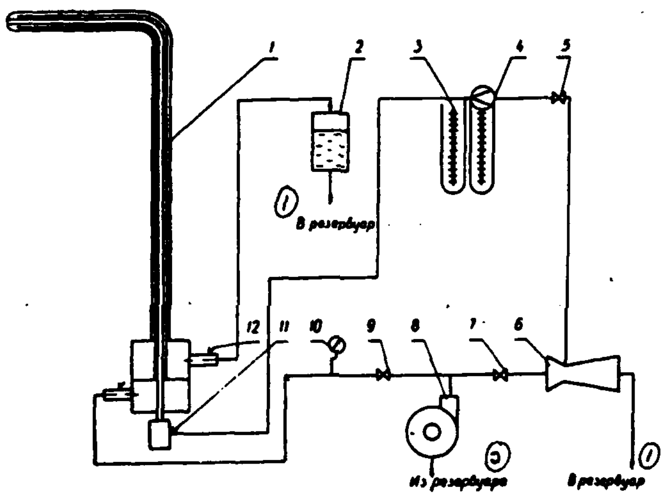


Figure 9. Layout for measuring the parameters of flow with a calorimetric probe. 1 - calorimetric probe; 2 - measuring container; 3 - U-shaped manometer; 4 - measuring diaphragm with a differential manometer; 5, 7, 9 - regulating valves; 6 - ejection vacuum pump; 8 - working pump; 10 - standard manometer; 11 - thermocouple; 12 - differential thermocouple.
Key: (1) To reservoir; (2) From reservoir.

Outer d of the probe - 4.25 , inner - 1.2 mm. The probe was cooled with water from the main pump (20 atm), therefore the maximum measured T did not exceed 3200°K. Flow rate of cooling water - 17 g/s.

The differential T in the range of 4-8°C was measured with a 4-junction copper-konstantan differential thermocouple. Gas in amounts up to 0.1 g/s was suctioned off by an ejection pump, also operating from the main pump.

Based on the measured T of the gas which was suctioned off and of the cooling water it was possible to determine the thermal balance of the probe with and without suctioning. Based on the differences of these variables the local enthalpies were determined and thereby the T on any section of the tube of the calorimetric probe.

In the case of T of the air flow lower than 1500°K the T profiles were measured with a standard platinum vs. platinum-rhodium thermocouple.

The profiles were measured at a distance l/d=18 from the entrance to the tube with d=20. Dynamic and static pressure was additionally measured with a ceramic tube.

On the outlet from the tube the readings of static pressure both in the case of a cold flow and a hot flow were practically equal to atmospheric. Based on the known dynamic pressure and T the velocity of flow was determined

$$w = c\sqrt{\frac{2\Delta P}{\rho}},$$

where: c - calibration constant, $\Delta P$ - dynamic head, $\rho$ - density of substance (kg/m$^3$).

The gas density was determined from the equation of state for pressure and T.

The results of the measurements of the dimensionless distributions of velocities are given in Figure 10.

The equation of the velocity profile [16] is presented in the form

$$\frac{w}{w_{max}} = \left(\frac{y}{R}\right)^{\frac{1}{n}},$$

where $\frac{w}{w_{max}}$ - dimensionless velocity, $y/R$ - dimensionless distances, $1/n$ - exponent, depending weakly on Re. For turbulent streams we accept n=7 [16].

Figure 10 also gives the results of the measurement of dimensionless profiles of T:

$$\frac{T-T_w}{T_{max}-T_w} = f\left(\frac{y}{R}\right).$$

As is evident from Figure 10, the T and velocity profiles based on their nature and absolute data come close to that of a turbulent stream and exceed the data obtained in a turbulent flow of a cold gas comparatively little [17].

Following integration of the measured profiles and a comparison with averaged data, obtained from the thermal balance, a satisfactory coincidence of results is obtained - up to ±5%.

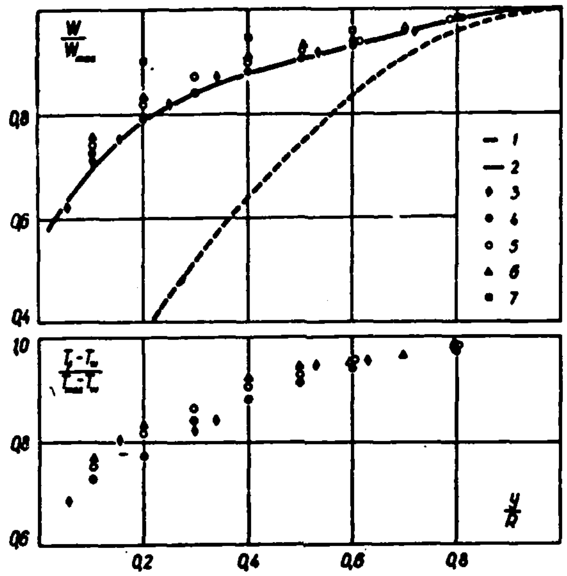

Figure 10. Distribution of dimensionless velocities and temperatures in a tube. Theoretical calculations: 1 - turbulent profile of velocities according to the "law of 1/7" [16]; 2 - laminar profile of velocities [16], measured profiles of velocities and temperatures: 3 - by a thermocouple and Pitot tube, $T_{max}$=1520oK, $w_{max}$=420 m/s, with a calorimetric probe: 4 - $T_{max}$=2600°K, $w_{max}$=700 m/s, 5 - $T_{max}$=2900°K, $w_{max}$=750 m/s, 6 - $T_{max}$=3300°K, $w_{max}$=700 m/s, 7 - with an optical electronic device [17].

## 5. Conclusions

1. A 300 kW experimental installation with electric-arc heating of different gases has been developed.

2. The volt-ampere characteristics of the heater were measured and at low currents they are ascending.

3. The T and velocity profiles were measured and they agree satisfactorily with the profiles of a turbulent stream.

4. On the basis of the measurements it was established that the installation on the whole can be used completely for continuous investigations of heat exchange and the behavior of high-temperature materials.

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