FTD-MT-24-370-68

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EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER IN THE REACTING BOUNDARY LAYER ON A POROUS PLATE

by

L. I. Tarasevich

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English pages: 13

Source: AN BSSR. Institut Teplo- i Massoobmena. Obshchiye Voprosy Teplo- i Massoobmena (General Problems of Heat and Mass Transfer), Nauka i Tekhnika, Minsk, 1966, pp. 37-47.

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Date 5 Nov 1968

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DATA HANDLING PAGE

01-ACCESSION NO. TT8501941	**98-DOCUMENT LOC**	**39-TOPIC TAGS** aerodynamic boundary layer, porous metal, chemical reaction, mass transfer, combustion chamber, heat exchanger, boundary layer heat transfer, wind tunnel
09-TITLE EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER IN THE REACTING BOUNDARY LAYER ON A POROUS PLATE		
47-SUBJECT AREA 20, 21		

42-AUTHOR/CO-AUTHORS TARASEVICH, L. I.	**10-DATE OF INFO** -----66
43-SOURCE AN BSSR. INSTITUT TEPLO- I MASSOOBMENA. OBSHCHIYE VOPROSY TEPLO- I MASSOOBMENA MINSK, NAUKA I TEKHNIKA (RUSSIAN)	**68-DOCUMENT NO.** FTD-MT-24-370-68
	69-PROJECT NO. 6040104

63-SECURITY AND DOWNGRADING INFORMATION UNCL, 0	**64-CONTROL MARKINGS** NONE	**97-HEADER CLASN** UNCL

76-REEL/FRAME NO. 1887 0603	**77-SUPERSEDES**	**78-CHANGES**	**40-GEOGRAPHICAL AREA** UR	**NO. OF PAGES** 13
CONTRACT NO.	**X REF ACC. NO.** 65-AT7014913	**PUBLISHING DATE** 94-00	**TYPE PRODUCT** Translation	**REVISION FREQ** NONE

STEP NO. 02-UR/0000/66/000/000/0037/0047	**ACCESSION NO.**

ABSTRACT

Intensive heat fluxes and high temperatures in contemporary combustion chambers and heat exchangers cause damage to the structural elements. The damaged elements can enter into chemical reactions with each other or with the external environment. Although a large number of theoretical studies dealing with this subject have been published, information concerning experimental investigations is practically not available. For this reason, the investigation of heat and mass transfer in the boundary layer and in the pressure of chemical reactions has a very important practical application. In the present study, an investigation was carried out in a special low-velocity wind tunnel with a closed 280 x 340 mm test section. The investigated porous plate was mounted on the lower wall of the test section. The air flow was maintained with a VVD-9 type high pressure centrifugal blower. The air flow rate, streamlining the plate, varied from 1 to 8 m/sec and was controlled by special dampers. The air temperature, which varied from 288 to 393°K, was stabilized with a deviation of ±0.3°C in the test section. Ethyl alcohol (C_2H_5OH) was used as the reacting liquid which was injected through the plate surface. The 196 x 60 x 3 mm porous metallic plate was divided into four sections. The first and second sections were 30 and 40 mm long, respectively, while the other two sections were each 60 mm long. The plate was made of a chrome-plated low-carbon steel powder with a 0.063 mm sphere diameter, a 11.7% total porosity, and an average pore diameter of 19μ.

The reacting liquid was fed to each section with a special injector. A → The study shows that heat liberated during the chemical reaction is partically transfered to the plate and is used to evaporate the reacting liquid. The remaining heat is dissipated by the air flow. The heat and mass transfer in the reacting laminary boundary layer takes place as follows: a) the reaction front is a fine region in the boundary layer at a certain distance from the porous surface; b) the oxidizer (ozygen) concentration in the region between the reaction front and the plate is insignificant. The fuel vapor content in region II (between the reaction zone and outside edge of the boundary layer) is also insignificant; c) the boundary layer contains inert components (N_2) and the reaction products (H_2O vapor, CO_2); d) a finite quantity of carbon monoxide is on the plate surface and it gradually decreases to zero at the reaction front; CO_2 is formed in the presence of oxygen and ethyl alcohol vapor; e) the reaction front practically coincides with the maximum temperature in the laminary boundary layer, and the minimum concentration of the reacting liquid vapor.

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

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. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER IN THE REACTING BOUNDARY LAYER ON A POROUS PLATE

L. I. Tarasevich

Porous, or evaporative, cooling of different apparatuses and devices (in certain cases) is accompanied by chemical reacting in the boundary layer. Intense heat fluxes and high temperatures in contemporary combustion chambers and heat exchange apparatuses cause, as a rule, destruction of their design elements. Here the elements of the destroyed surface can enter into chemical reactions among themselves or with the environment.

Therefore, the most important problem at present which has great practical value is the investigation of the process of heat and mass transfer in the boundary layer during chemical reactions.

There are many theoretical works which have been dedicated to this problem, the most complete survey of which is given in [1-7, 9, 10], whereas experimental investigations are practically absent, with the exception of sources [8, 11].

The basic goal of the experimental investigation of the examined process is to establish the relationship between the surface temperature of a porous metallic plate, the temperature in the reaction zone, the position of the reaction front and mass flow rate of an injected combustible liquid, and also to determine the concentrations and enthalpies in the reacting boundary layer under different hydrodynamic and temperature rates of the incident airflow.

An experimental investigation of the process of heat and mass transfer in the reacting boundary layer was conducted on a special experimental device (Fig. 1), constituting low-speed closed wind tunnel of constant operation with closed working area and transverse rectangular section of 280 × 340 mm.

In the lower wall of the working area of the wind tunnel the investigated porous plate was built in.

The wind tunnel worked according to an open scheme, which was carried out with the aid of special regulating slide valves. Work of the wind tunnel on a closed scheme would lead to the accumulation of a large quantity of reaction products in the pipeline and would introduce great error in the determination of concentrations in the reacting boundary layer.

The airflow in the wind tunnel moves with the aid of a centrifugal, high pressure fan of type VVD-9, joined with a 27 kW electric driving motor.

To eliminate the vibration which is transmitted from the fan to the wind tunnel, flexible adapters were made which connect the inlet and pressure pipes of the fan with the tunnel.

The speed of the airflow, incident on the plate, $u_\infty = 1$-8 m/s, was regulated by the special slide valves.

The dynamic head of the airflow was measured by a pneumatic Pitot-Prandtl metric combinational cap and a liquid, multirange cistern micromanometer with a slanted tube of type MMN and accuracy class of 0.5. A combined Pitot-Prandtl cap was fixed in the wind tunnel at a certain distance from the working section upwards along the airflow in such a fashion that the measuring transducers rendered no influence on the cap. The air in the wind tunnel was heated by a four-section electrical air heater with power of 55.2 kW. The last section of the heater (downwards along the flow) was connected

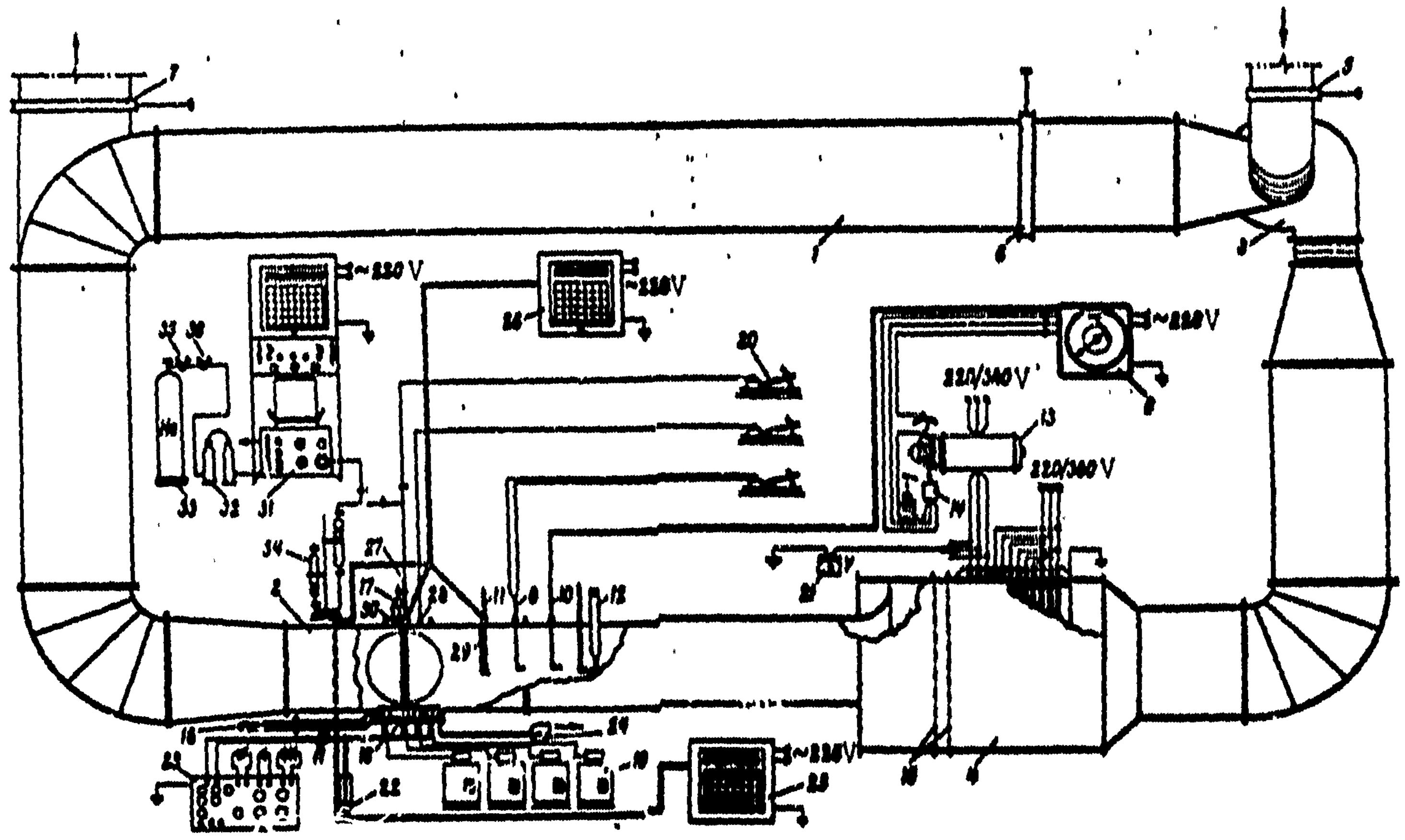

Fig. 1. Diagram of the experimental device: 1 - closed pipeline; 2 - working area; 3 - fan; 4 - electroair heater; 5, 6, 7 - regulating slide valves; 8 - Pitot-Prandtl tube; 9 - potentiometer EPD-12; 10 - temperature transducer; 11 - mercury thermometer; 12 - psychrometer; 13 - voltage regulator; 14 - servomechanism, type PR-1; 15 - levelling grids; 16 - experimental body; 17 - traversing probe; 18 - feed of cooling water; 19 - scales VTK-500; 20 - micromanometer MMN; 21 - voltmeter; 22 - thermostat; 23 - potentiometer R-306; 24 - fan; 25 - potentiometer EPP-09 M3; 26 - potentiometer EPP-09 M1; 27 - total pressure tube; 28 - pipe connection for sampling static pressure; 29, 30 - thermocouples; 31 - chromatograph, type KhL-3; 32 - gas desiccant; 33 - tank with helium; 34 - blowing system for gas sampler; 35, 36 - reduction valves: hydrogen and acetylene.

to an automatic temperature control system, while the other three sections had a separate connection to the power-supply network. Maximum power of the adjustable section of the air heater was 8.6 kW. The automatic adjustment system consisted of a temperature transducer, which was a chromel-Copel thermocouple, and automatic electronic regulating and self-recording potentiometer of the EPD-12 type of accuracy class 0.5, and a voltage regulator - an asynchronous engine with a braked rotor. Turn of the rotor is carried out by a servomechanism of the PR-1 type. Thus, in the experimental device both automatic "smooth" and "step" temperature adjustments were anticipated. The assigned airflow temperature in the working area was stable and deviations were ±0.3°C. On the outside, the wind tunnel was covered by miltilayer thermal insulation.

Temperature of the incident flow of air, which changed within limits of from 288 to 393°K, was measured by a copper-constantan and chromel-Alumel thermocouple in accordance with the recording of readings by the automatic self recording potentiometers of type EPP-09 and EPP 09 M1. The accuracy class of these instruments is 0.5. Furthermore, temperature of the airflow was measured by a mercury thermometer with a scale value of 0.1°C. Temperature measurement of the internal walls of the working area of the wind tunnel was produced by copper-constantan thermocouples, built into the vertical and horizontal walls, connected to a potentiometer of the EPP-09 type. Stabilization of velocity and temperature of the air flow in the tunnel was carried out by two correspondingly selected grids, set at a distance of 0.3 m from the air heater, and also by a smooth convergent entrance, made in the form of a flat lemniscate, located near the grids. The length of the stabilizing section, i.e., the distance from the smooth convergent entrance to the working area of the tunnel, was 2.5 m, which was sufficient for complete levelling off of the airflow.

To determine the uniformity and stability of the airflow in the working area of the wind tunnel, both the hydrodynamic and the thermal fields were thoroughly measured. Irregularity of the field of averaged velocities and temperatures in the region occupying more than 80% of the section of working area of the tunnel does not exceed 1.5-2% of the flow rate of air and temperature on the axis of the tunnel. The turbulence of the incident airflow was also measured with the aid of a hot-wire anemometer of the ATA-2 type with ac feedback, working according to the constant filament temperature method. A gold-plated tungsten filament with a diameter of 0.018 mm and length of 3 mm, possessing a very great time constant of thermal inertia, was heated by high frequency alternating current.

The degree of turbulence of the incident airflow, under our conditions of conducting the experiment, was $\varepsilon = 0.5\%$.

In the working area of the wind tunnel, for visual observations of the process which was occurring in the reacting boundary layer on the porous plate (and also for convenience of service), in the lateral walls heat-resistant LK-5 glasses were installed with a diameter of 270 mm and hermetic closure.

As the reacting liquid, which was injected through the plate surface, ethyl alcohol (C_2H_5OH) was used.

The experimental body (Fig. 2) was a porous metallic plate with dimensions of 196 × 60 × 3 mm, divided into 4 sections. The first section had a length of 30 mm ; the second – 40 mm, the last two – 60 mm each. Every section of the porous metallic plate was soldered onto the nickel-plated brass body. Thus a dense hermetic connection was created with the wall of the body, precluding the leakage of liquid.

For manufacture of the working plate metallic porous samples were used with a thickness of 3 mm, made from a spherical powder of chrome-plated low carbon steel with a diameter of particles of 0.063 mm. The porous material utilized possessed good structural characteristics, uniform porosity throughout the mass of the sample and sufficient mechanical strength. Porous plates made from particles Ø 0.063 mm, had a general porosity of 11.7%, and the average diameter of the pores was 18 μm.

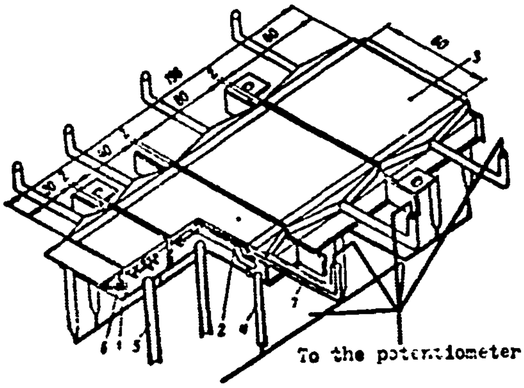

Fig. 2. Experimental body: 1 - brass body, covered with nickel; 2 - porous metallic plate; 3 - copper-constantan thermocouple; 4 - pipe connection for feeding the reacting liquid (ethyl alcohol); 6 - textolite accumulator; 7 - air bubble drainage pipe connection.

Air bubbles formed under the plate escaped through special draining tubes. Through these tubes copper-constantan thermocouples were drawn out, which were sealed inside the experimental body and also on the internal and external surfaces of the porous metallic plate.

The combustible liquid was fed to every section through special pipe connections. The flow rate of ethyl alcohol, sent to a section, was recorded by the weight method by means of highly sensitive electrical square scales of the VTK-500 type with a scale value of 0.1 g. In the ends of each section of the porous plate there were nozzles, joined by a rubber tube with graduated glass tubes, thanks to which the position of the level of the evaporation zone in the porous plate could be visually established, depending upon the different hydrodynamic and temperature modes used in the experiment.

Under the examined conditions the level of the evaporation zone practically coincided with the surface of the porous plate. Inasmuch as the experimental body and the tank with the reacting liquid, set on VTK-500 scales, were practically connecting vessels, the tank section was calculated in such a manner so that its rise, caused by the consumption of injected substance, ensured the assigned backwater of evaporating liquid and so that the level of the evaporation zone coincided with the porous plate surface.

To the leading edge of the experimental body an accumulator with a length of 10 mm was joined, made of thermal insulation material. Through a slot in front of the accumulator sucking of the boundary layer was produced for the purpose of excluding the influence of the development of flow.

Surface temperature of the metallic porous plate was measured by copper-constantan thermocouples made of wire with a diameter of 0.15 mm. For mounting the thermocouples, in the porous metallic plate holes were drilled, then the wires were stretched and they were welded. The head of the thermocouple was placed in a hole of somewhat smaller diameter than the diameter of the wire joint. Then the thermocouple head was pressed into this hole and mounted flush with the surface of experimental body. In all, in the experimental body 27 copper-constantan thermocouples were mounted. Ten thermocouples were located in checkerboard order on the external surface of the porous plate; of them four (one thermocouple from every section) were led out to a low-resistance dc laboratory potentiometer of the R-306 type, and the others – to a potentiometer of the EPP-09 type. Thus dual control of the measurement of surface temperature of the porous plate was organized. From the internal side of the porous plate, in each section one thermocouple was mounted, as well as thermocouples throughout the depth of the porous plates. The temperature of the combustible liquid at the entrance to the porous plate of each section was measured by copper-constantan thermocouples. The temperature of the cooling water, passing through the coolers, at the entrance and exit of each section was measured by copper-constantan thermocouples, the readings of which were recorded by a low-resistance dc laboratory potentiometer of the R-306 type. Cooling water was fed to each section from a water line network through a distributive manifold. On every distributive rubber hose valves were mounted which allowed regulating the flow rate of cooling water and, consequently, the temperature of the reacting liquid. The flow rate of cooling water, flowing through each section, was determined by the measuring method.

The average surface temperature of the porous plate was calculated according to measured local temperatures for each part of the section. The parameters of the boundary layer – velocity, temperature and concentration – were measured simultaneously at one point, inasmuch as the total pressure tube (that of selected concentrations of tests) was joined with a chromel-Alumel thermocouple having a diameter of the wires of 0.15 mm in one measuring probe. In order to avoid catalytic phenomena, the chromel-Alumel thermocouple was insulated by borax. The measuring probe moved both in the longitudinal and in the transverse directions by means of a traversing probe, which was a micrometric screw with a scale value of 0.01 mm.

Velocity in the boundary layer was measured by a total pressure tube and by measurement of static pressure. The total pressure tube, made of stainless steel, had a tip with an internal diameter of 0.43 mm. Static pressure on the experimental section was measured through holes with a diameter of 0.35 mm, drilled in the lower and lateral walls of the working area of the wind tunnel. Readings of total and static pressure were fixed by a multirange cistern micromanometer of the MMN type.

The profile of the concentrations in the reacting boundary layer is determined by sampling gas specimens. A separator of gas specimens, made of stainless steel, was designed so that its aperture, with a diameter of 0.43 mm, was expanded to a diameter of 2.5 mm for the purpose of extinguishing the chemical reaction in the tank of gas specimens. A system for cooling the separator was foreseen, which was a water jacket, inside which there was a total pressure tube with a diameter of 2.5 mm. Into the water jacket a second tube was introduced of the same diameter, which carried cooling water. The cooling water was removed through the pipe connection, welded into the water jacket.

The gas specimens were analyzed at room temperature; consequently, there were stable molecular substances present such as carbon dioxide (CO_2), oxygen (O_2), carbon oxide (CO), nitrogen (N_2), and a sum of hydrogen and critical hydrocarbons ($H_2 + C_nH_{2n+2}$). Taking the gas specimen from the separator was done by a medical syringe, where the value of the removed volume of the specimen did not exceed 1-1.5 cm^3.

Before sampling the gas specimen and during it, the probe systems were ventilated with the aid of a special ventilation system, consisting of two burettes, rubber tubes and regulating valves. An analysis of the gas specimen, taken in the reacting boundary layer, was produced by a laboratory chromatograph of the KhL-3 type.

In the work of the chromatograph KhL-3 helium was used, which was the gas carrier and which was located in a tank under pressure of 150 atm. The smooth drop of high pressure from 150 to 1.5-2 atm was realized with the aid of two reduction valves, one hydrogen and the other acetylene, mounted on the tank; finer pressure control was realized by means of a needle valve. The necessary flow rate of the gas carrier was controlled by a rotameter. For chromatogram readout the instrument was calibrated for the gases being investigated. Simultaneously with measurements on the type KhL-3 chromatograph, an analysis was made of the gas samples on a type VTI-2 (GOST 5433-56) gas analyzer. Error in the analysis of gas samples by this gas analyzer did not exceed ±0.1%.

Figure 3 shows the distribution of temperature T and the concentrations by sections in the reacting laminar boundary layer on the porous metallic plate during the injection of a combustible liquid. The reacting liquid (ethyl alcohol) constitutes hydrocarbons; therefore, its boiling point is considerably lower than the temperature which corresponds to the beginning of reaction. Since during the experiment the surface temperature T_w of the porous metallic plate, from the side of the incident airflow, is equal or insignificantly exceeds the boiling point of the reacting liquid, then the zone or reaction front cannot be located on the plate

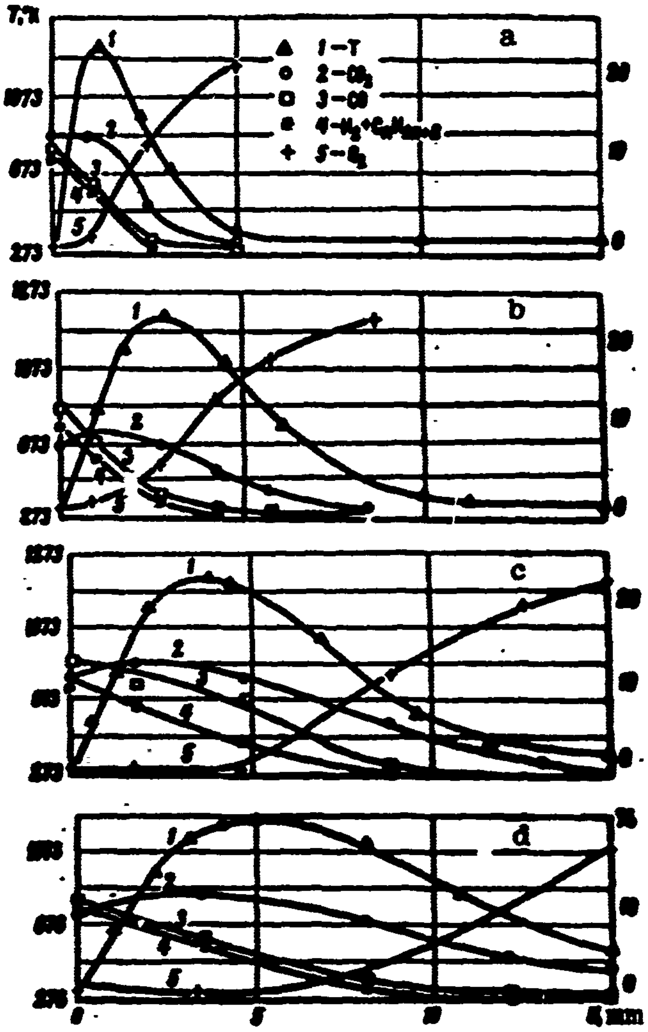

Fig. 3. Distribution of temperature and concentration by height in the reacting boundary layer: $T_\infty = 303^\circ K$; $Re_\infty = 0.4 \cdot 10^5$; the reacting liquid is ethyl alcohol: a) I section x = 25 mm, b) II section x = 62 mm; c) III section x = 114 mm; d) IV section x = 176 mm.

surface. Consequently, the chemical reaction must occur in the gas phase and the front of the reaction is located at a certain distance from the metallic plate surface.

The position of the front of chemical reaction η_* is characterized by the fact that the vapors of the reacting liquid and oxygen approach the zone of reaction from opposite sides.

Measurement of temperature in the reacting laminar boundary layer on the porous metallic plate shows separation of the front of reaction from the surface of porous plate downwards along the flow.

Oxygen (O_2) diffuses in the direction of the drop of concentration, i.e., from the external flow to the front of chemical reaction, where it is almost completely expended. Oxygen penetrates to the surface of the porous metallic plate nevertheless, since its concentration at the surface of the porous plate is nowhere equal to zero. Carbon dioxide (CO_2), forming in the course of chemical reaction, diffuses from the zone of chemical reaction into the external airflow and toward the porous wall. In region I, i.e., between the surface of the porous metallic plate and the front of reaction, diffusion of the vapors of the reacting liquid occurs toward the front of reaction, where they are almost completely expended. In view of the fact that in region I the content of O_2 is insignificant, then probably the CO_2 will react with the vapors of the reacting liquid, as a result of which CO will be formed, which diffuses toward the front of the chemical reaction. In this way H_2 can be formed, the concentration of which in region I is insignificant. Despite the fact that neither carbon oxide nor carbon dioxide will be formed on the surface of the porous plate, their concentrations on the surface of the plate due to the above examined causes compose a finite quantity.

The heat separated during chemical reaction and during the burning of vapors of the reacting liquid is partially brought to the surface of the porous plate and is expended on heating the frame of the plate and on evaporation of the reacting liquid. The remaining part of the heat is taken away into the external incident airflow.

As can be seen from Fig. 3, the position of the front of chemical reaction can be determined by the maximum of temperature in the reacting laminar boundary layer.

On the basis of the above it may be concluded that the process of heat and mass transfer in the reacting laminar boundary layer occurs in the following way:

a) the reaction front is a practically thin zone (surface), located in the boundary layer at a certain distance from the porous surface (in the leading edge of the experimental body $\eta_* = 0$). The value η_* depends on coordinate x, i.e., $\eta_* = \eta_*(x)$;

b) in the zone between the reaction front and the plate (region I), the concentration of oxidizer (in examined case, oxygen) is insignificant. In region II (between the reaction zone and the external edge of the boundary layer) the mass content of vapors of the combustible liquid also is insignificant;

c) in the entire volume of the boundary layer there are inert components (N_2) and products of reaction (vapors H_2O, CO_2);

d) the content of carbon oxide has a finite quantity on the surface of the body and decreases monotonously, practically attaining zero in the front of the reaction; the formation of CO_2 in this region is caused by the reaction (under the conditions of an insignificant content of oxygen) of vapors of ethyl alcohol with carbon dioxide;

e) from an analysis of Fig. 3 it follows that the position of the front of reaction of η_* practically coincides with the temperature maximum in the reacting laminar boundary layer and the minimum of concentration of vapors of the combustible liquid.

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Institute of Heat and Mass Transfer,
Academy of Sciences
Belorussian SSR,
Minsk