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EXPERIMENTAL INVESTIGATION OF FUEL EVAPORATION IN THE VAPORIZING ELEMENTS OF COMBUSTION CHAMBERS

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1. Experimental Set-Up and Methods of Investigation

A sketch of the experimental set-up is presented in Fig. 1. /180* The warm up of the walls of the vaporizing element is done in a special heating set-up. The chamber of the apparatus in which the vaporizing element is placed is filled with tin. The temperature of the wall was measured with a contact mercury thermometer. Using this thermometer made it possible to maintain the required temperature in the wall of the vaporizing element automatically concurrently during the experiments. The spatial arrangement of the vaporizing elements in the warm-up apparatus was similar to the actual conditions which obtain in the combustion chambers in an engine. Unevaporated fuel flows along the walls of the vaporizing element and occurs in the current in the form of drops. In connection with this, the apparatus for separating out the unevaporated fuel consisted of two parts: film removing rings for removing unevaporated fuel film from the walls of the pipe and a separator suspended in the current of the liquid phase. The unevaporated fuel which was collected was weighed by analytic weights. Fuel evaporation was studied not in clean air

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* Numbers in the margin indicate pagination in the foreign text.

PREFACE

The vaporizer type of combustion chamber is becoming more and more frequently used in gas turbine engines. The use of such combustion chambers in small gas turbine engines is especially interesting [1]. Due to the fact that the fuel in the vaporizing combustion chamber is fed into the combustion zone in a vaporous state, the problem of burning the fuel effectively may be solved by relatively small heat pipes. Fuel evaporation occurs in special vaporization elements in the combustion zone. In order to make accurate selections of the geometric and gas dynamic parameters of the vaporizing elements, experimental data on the processes which occur in the vaporizing elements must be available. Establishing these processes has been the task of investigations. The program of investigations comprises the study of the effects of the following factors on the degree of fuel evaporation: the air surplus coefficient in the vaporizing element (α), temperature (t_A) and velocity (V_A) of the flow at the entrance to the vaporizing element, the temperature of the wall (t_W) of the vaporizing element, the fuel feeding pressure. The degree of fuel evaporation (ϕ) was determined as the percent ratio of the amount of evaporated fuel at the exit from the vaporizing element to the entire fuel supplied

$$\varphi = \frac{G_{in}}{G_T} 100\%.$$

A method based on removing unevaporated fuel from the air-fuel mixture outside the vaporizing element [2] was used to determine the value of ϕ.

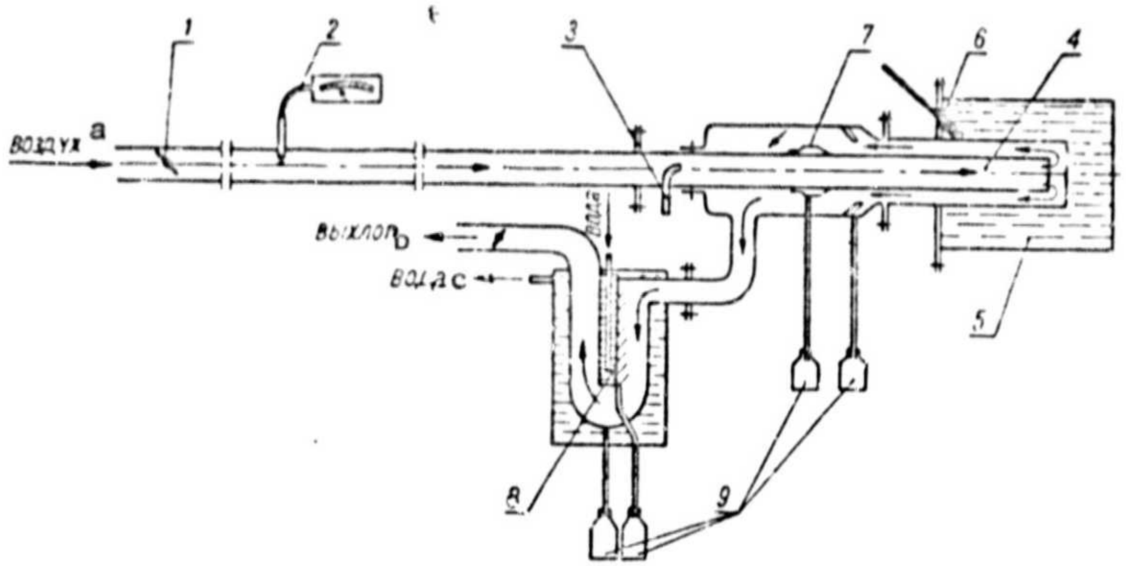

Fig. 1. Sketch of the experimental apparatus.

1--regulator of discharge of air through the vaporizing element; 2--thermocouple which measures the temperature of the air current; 3--fuel nozzle; 4--vaporizing element; 5--chamber for warming up the walls of the vaporizing element; 6--thermocouple which measures the temperature of the wall of the vaporizing element; 7--film removing rings for removing unevaporated fuel film from the walls of the pipe; 8--separator for the suspended liquid phase a--air; b--exhaust; c--water

but in combustion products, some of which were led from the combustion chamber to the vaporizing element. Inasmuch as the value of the air surplus coefficient exceeded $\alpha > 10$ we may consider that such a solution to the question of air warm-up does not distort the experimental results. Investigations were conducted with two types of vaporizing elements: L-shaped and coaxial (Fig. 2).

In the course of the experiments the temperature in the current at the entrance to the vaporizing element varied within the range 30-350°C, the flow velocity within the range 10-45 m/s and the temperature of the walls of the element within the range 200- /181 500°C. Fuel discharge varied within a wide range which corresponded to the variation in the air surplus coefficient α from 0.05 to 1.6. Detachable nozzles having feeding aperture diameters = 0.3; 0.35; 0.4; 0.45; 0.5 mm were used in studying the effect of fuel feeding pressure. The fuel feeding pressure varied within the range p_T = 10-6000 kN/m^2. The fuel used during the experiments was kerosene.

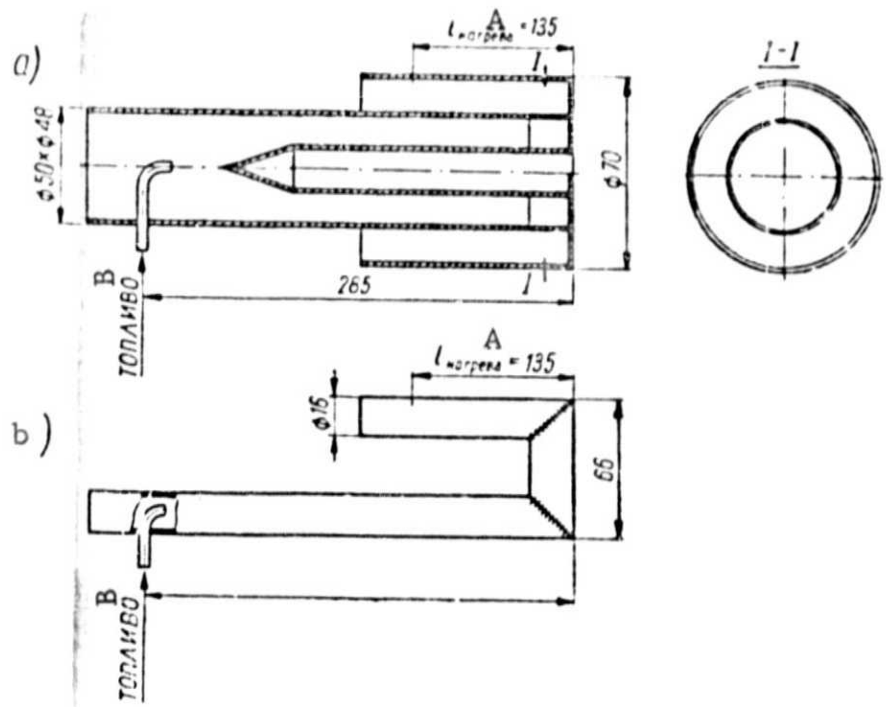

Fig. 2. Sketches of vaporizing elements studied

a--coaxial; b--L-shaped
A-- $t_{warm\text{-}up}$; ; B--fuel

Results of the Experimental Investigation and their Analysis

2.1 Results of the Study of the L-Shaped Vaporizing Element

The dependences found (Fig. 3) demonstrate the increase in the degree to which fuel is evaporated with an increase in α. An increase in α denotes (with defined flow conditions) a decrease in the amount of fuel exerted on a unit of the surface of the vaporizing element and consequently, an improvement in the conditions of fuel evaporation. However, the increase in ϕ is relatively slight within the range of changes in α studied. The degree of fuel evaporation was increased by an increase in the

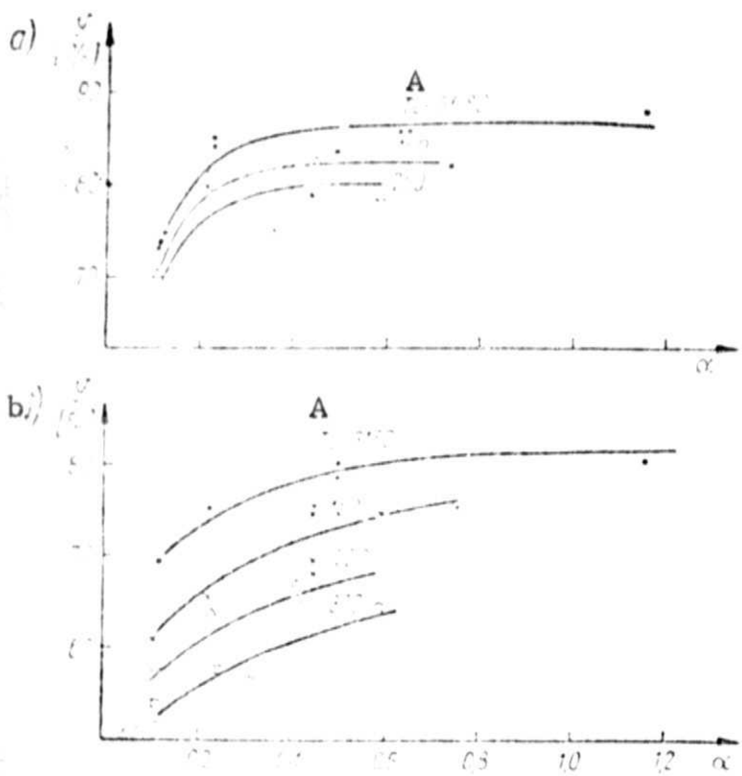

Fig. 3. Dependence of the degree of fuel evaporation on the air surplus coefficient and the temperature of the air flow at a flow velocity V_A 20 m/s

a--t_W =200°C; b--t_W = 500°C

A--T_A

flow velocity from V_A = 10 m/s to V_A=45 m/s (Fig. 4). An increase in ϕ with an increase in velocity is especially noticeable with a high temperature in the walls of the vaporizing element. The results of investigations also indicate that when other factors are constant the degree of fuel evaporation decreases with an in- /183 crease in the flow temperature within the range t_A =30-350°C. Thus, for example, when α = 0.5; t_W = 500°C and V_A = 20 m/s a change in the temperature of the flow at the entrance to the vaporizing element from 33°C to 330°C leads to a decrease in ϕ from 76% to 58%. The flow velocity in the vaporizing element changes

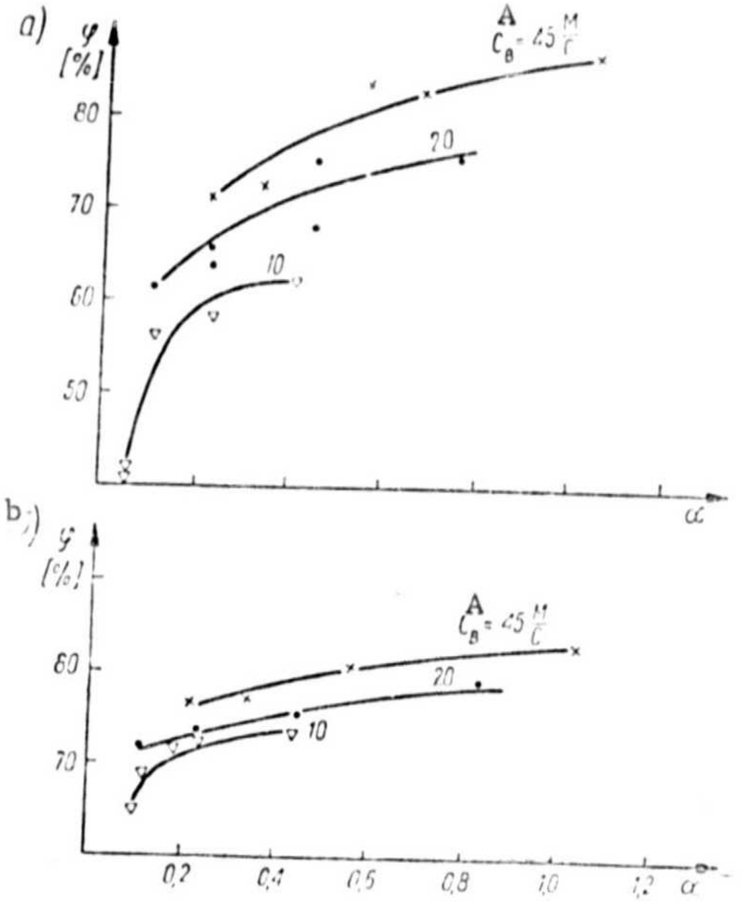

Fig. 4. Dependence of the degree of fuel evaporation in the L-shaped vaporizing element on the air surplus coefficient and flow velocity (t_A =150°C)

a--t_W= 500°C; b--t_W= 350°C
A--V_A=45 m/s

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with the path of the flow due to an increase in temperature. The highest values for the temperature increments in the mixture and, correspondingly, the greatest acceleration at the exit from the vaporizing element, were found at the lowest values, namely t_A= 33°C (Fig. 5). With an increase in the temperature of the wall

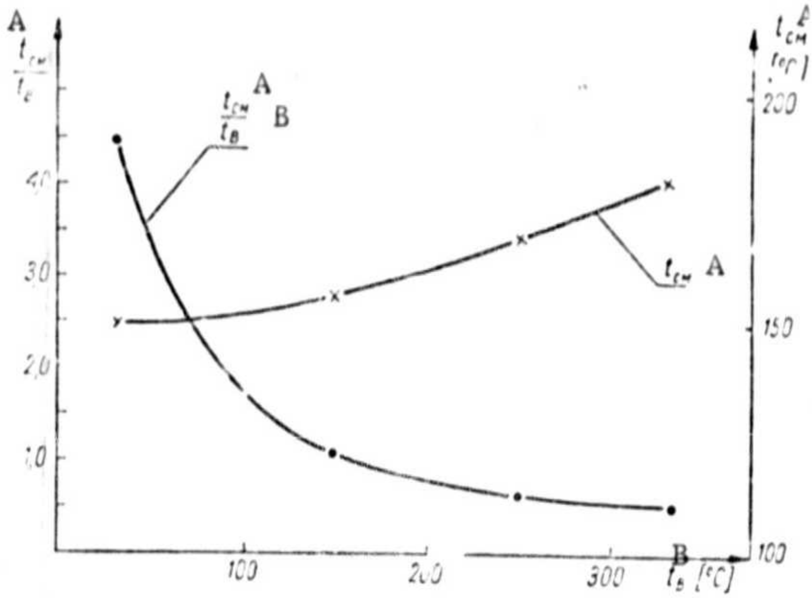

Fig. 5. The dependence of the temperature of the mixture at the exit from the vaporizing element t_{MI} and the ratio t_{MI}/t_A on temperature (t_A)

t_W=350°C; V_A=20 m/s; α=0.1-0.8

A--t_{MI}; B--t_A

within the range t_W = 200-500°C with other factors constant (Fig. 6), the degree of fuel evaporation decreases and the most intense drop in ϕ is observed in regions of small values of α and high /184
values of t_A. The maximum value of ϕ found during the experiments involving the L-shaped vaporizing element was ϕ = 88% ($0.1 \leq \alpha \leq 1.2$).

2.2 Results of the Study of the Coaxial Vaporizing Element

An increase in the air surplus coefficient in the vaporizing element for all values of V_A, t_A and t_W led to an increase in the degree of fuel evaporation (Fig. 7). We must note that the func-

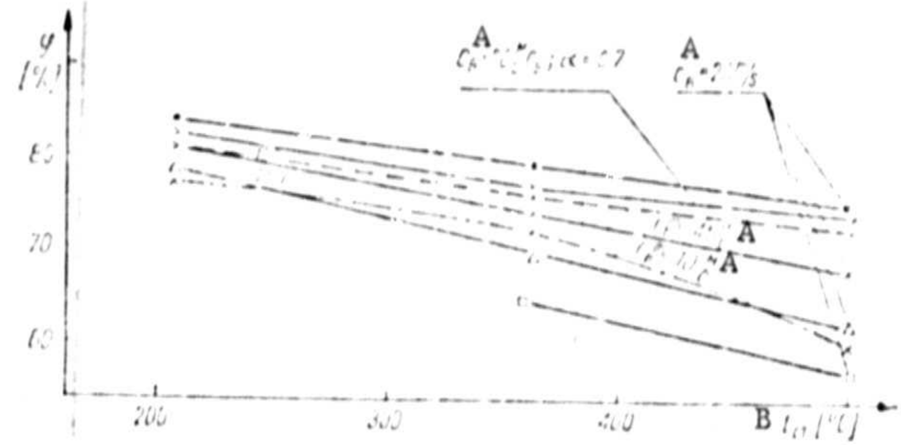

Fig. 6. Dependence of the degree of fuel evaporation in the L-shaped vaporizing element on the temperature and velocity of flow (α = 0.3)

• --t_A 30°C, ×--150°C, △--250°C, □--350°C
A--V_A; B--t_W

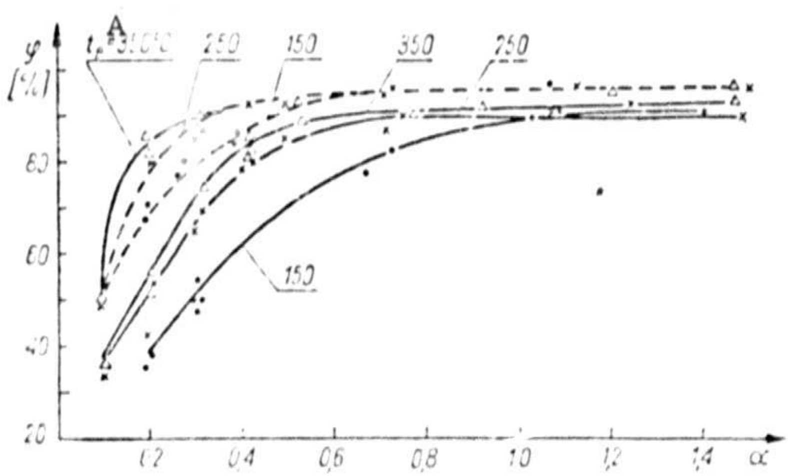

Fig. 7. Dependence of the degree of fuel evaporation in the coaxial vaporizing element on the air surplus coefficient, temperature and velocity of flow at t_W=500°C

- - - - - V_A=1- m/s; ——— V_A= 20 m/s
A--t_A

tion $\phi = f(\alpha)$ characterizes the intensity of the increase in ϕ with an increase in α in the range of small values of α. With values of α far from a defined $\alpha_{\Gamma p}$ the degree of fuel evaporation practically does not depend on the air surplus coefficient. The value of $\alpha_{\Gamma p}$ depends on V_A, t_A. An increase in the velocity and temperature of the flow leads to a decrease in $\alpha_{\Gamma p}$(thus when t_W=350°C and t_A=170°C for V_A=10 m/s, $\alpha_{\Gamma p}$ 0.9 and for V_A= 20 m/s $\alpha_{\Gamma p}$ =0.4; when t_W=200°C and V_A= 20 m/s for t_A=170°C $\alpha_{\Gamma p}$=0.95 and for t_A =350°C $\alpha_{\Gamma p}$=0.5). An increase in the flow velocity from 10 m/s to 30 m/s led to an improvement in fuel evaporation. The flow velocity had an especially evident effect when $\alpha<\alpha_{\Gamma p}$ (Fig. 7). The effect of flow temperature on the degree of fuel evaporation also shows up mainly within the range $\alpha<\alpha_{\Gamma p}$, while when V_A=const and t_W=const the curves $\phi=f(\alpha)$ for t_A= const either converge (Fig. 8a) or intersect in the vicinity of the largest $\alpha_{\Gamma p}$ for these lines ($\alpha_{\Gamma p max}$) (Fig. 8b). When $\alpha<\alpha_{\Gamma p\,max}$ an increase in the flow leads to an increase in ϕ, while for $\alpha>\alpha_{\Gamma p\,max}$ the temperature either does not affect ϕ or affects it inversely, an increase in t_A leads to a reduction in ϕ. The temperature of the wall evidently affects the degree of evaporation only in the range $\alpha<\alpha_{\Gamma p}$ (for all values of t_A and V_A during the experiments). The data obtained indicate the presence of the maximum value of ϕ /186
in the range of t_W under consideration, while the temperature of the wall which corresponds to this value of ϕ increases with an increase in the temperature of the air flow (for t_A=150°C, α=0.3, V_A =10-20m/s the maximum value of ϕ is attained when t_W=350°C).

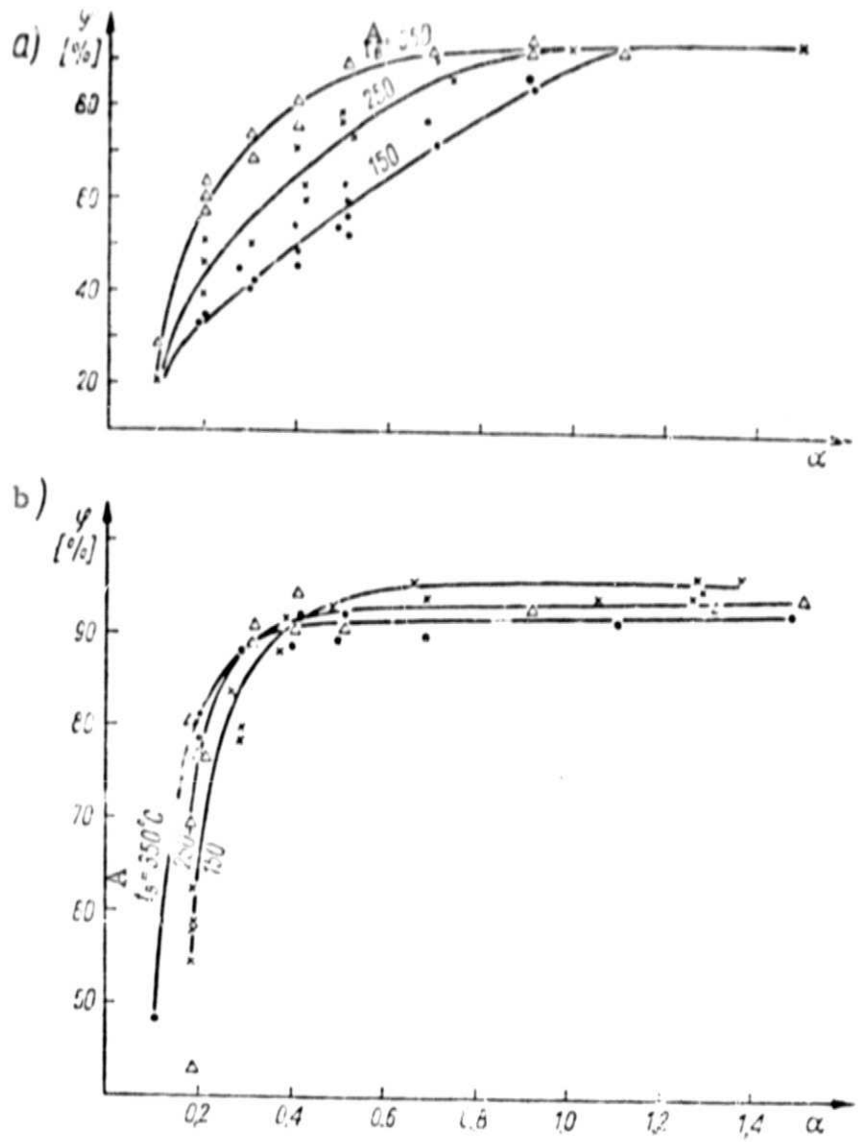

Fig. 8. The dependence of the degree of fuel evaporation in the coaxial vaporizing element on the air surplus coefficient and the flow temperature

a) t_W=200°C, V_A=20 m/s; b) t_W=350°C, V_A=20 m/s
A--t_A

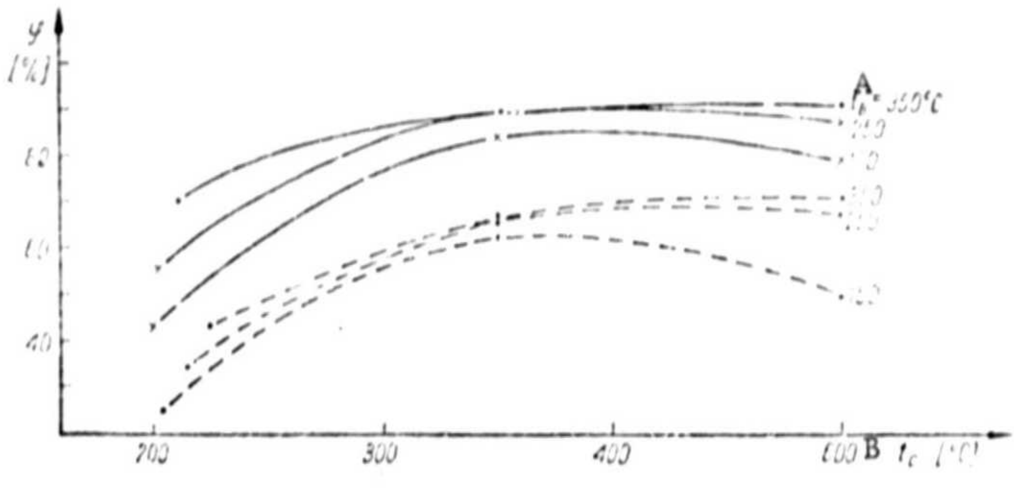

Fig. 9. The dependence of the degree of fuel evaporation in the coaxial vaporizing element on the temperature of the wall for α=0.3

------ V_A=10 m/s, — — — V_A=20 m/s
A--t_A; B--t_S

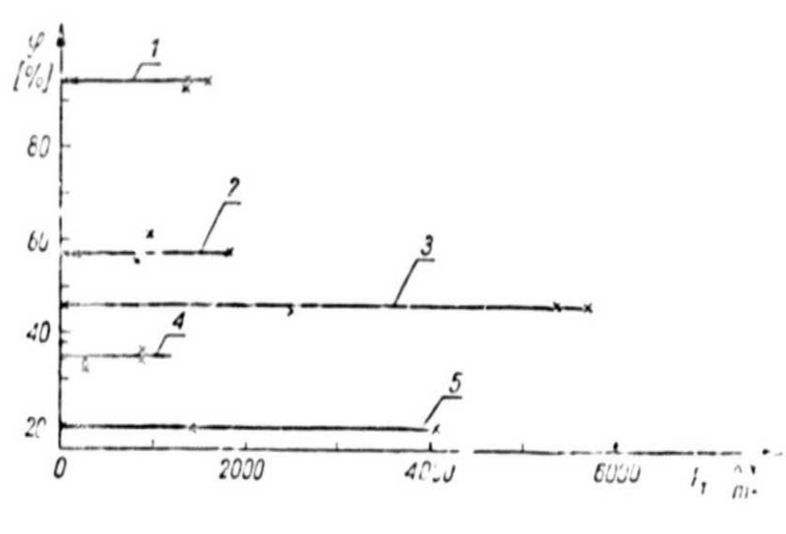

Fig. 10. The effect of the fuel feeding pressure on the degree of fuel evaporation

1--α=0.645, V_A=20 m/s, t_W=350°C; 2--α=0.284, V_A=10 m/s, t_W=350°C; 3--α=0.258, V_A=20 m/s, t_W=200°C; 4--α=0.406, V_A=10 m/s, t_W=200°C; 5--α=0.2, V_A=10 m/s, t_W=200°C

Results of the investigation of the effect of the fuel feeding pressure in the vaporizing element are presented in Fig. 10 and indicate that fuel feeding pressure, which varied within the range $p_T = 10\text{-}6000 kN/m^2$, did not affect ϕ. These data also confirm the fact that a large part of the fuel flows along the walls of the vaporizing element. The maximum value of ϕ obtained during the experiments was 97% for the coaxial vaporizing element.

2.3 General Remarks

The process of evaporation in the vaporizing element is very complex since several phenomena occur simultaneously: the evaporation of a film of fuel and drops of fuel with the presence of a flow in the surrounding medium and also the evaporation of drops of fuel in the flow. There are well known studies in which the individual phenomena have been discussed and in which criterial dependences have been established which define the processes of heat and mass exchange during the evaporation of drops in an air current and on a hot wall. However, the experimental data presented in these studies are insufficient to yield a precise analysis of the dependences found as a result of the experiments described. Without additional investigations it is impossible to determine the character of the flow of fuel in the vaporizing element, however, on the basis of [3] we may assume that it is very complex and that it depends on the shape of the vaporizing element and exerts a substantial effect on the degree of fuel evaporation.

The effect of the flow velocity on the evaporation of fuel is not uniform. First of all, on the one hand the rate of fuel evaporation is determined by the rate of diffusion of fuel vapors /187 formed on the surface of the surrounding medium into the medium and by the rate of heat transfer from the surrounding medium to the fuel. With an increase in the flow velocity the rate of diffusion of the vapors from the surface of the fuel increases due to an increase in the turbulent diffusion coefficient D_T $l \cdot c'=$ and $c = \varepsilon_T \cdot c'$ (c_T, the intensity of turbulence, depends mainly on the construction of the vaporizing element and we may consider that $\varepsilon_T = const$ during the experiments). There is also an intensification of the process of heat exchange between the fuel and the surrounding medium in relation to the increase in the number $Re = c \cdot d/\nu$ and, accordingly, criteria Nu_T and Nu_D which characterize the processes of heat and mass exchange. This concerns both the fuel in the air flow in the form of drops and the fuel which flows along the walls. On the other hand, the increase in the flow velocity (under experimental conditions) was related to an increase in the massive discharge of air and the discharge of fuel proportional to it which fed into the vaporizing element (consequently, the amount of fuel which was exerted on a unit of surface of the vaporizing element increased). Simultaneous with an increase in the flow velocity the length of time that the fuel remained in the vaporizing element decreased, this concerned mostly the drops which move with the flow. In addition, with high flow velocities the film of fuel may be stripped from the walls and the conditions of heat transfer from the hot walls to the fuel may deteriorate. The fact that a large part of the fuel flows along the walls of the vaporizing element undoubtedly affects the character of the dependences of the degree of fuel evaporation on the flow velocity which were considered above. To a slight extent an increase in the flow velocity results in an increase in the flow velocity of the fuel, while the difference between the velocities of fuel and air flow affects the processes of diffusion and heat exchange positively.

The effect of the temperature of the air flow on the process of fuel evaporation in the vaporizing element is complex. On the one hand an increase in air temperature results in an increase in the value of the turbulent diffusion coefficient, an increase in the temperature difference between the flow and the fuel and a decrease in the massive discharge of air (at constant velocity), and, when $\alpha = \text{const}$, a decrease in the total amount of fuel fed into the vaporizing element. On the other hand an increase in temperature results in an increase in the specific heat capacity of the air and fuel vapors, an increase in the viscosity of the flow and a decrease in the number Re.

At a defined flow temperature the temperature of the wall of the vaporizing element determines the possible heat flow from the wall to the fuel-air flow ($Q = F\alpha\Delta t$). An increase in t_W consequently has a positive effect on the process of fuel evaporation in the air flow. However, a large value for fuel evaporation on the walls of the vaporizing element shows up in the value of ϕ. As is well known, it was established during investigations of the rate of evaporation of drops on a preheated plate [4] that there is a set temperature of the plate for which the evaporation time of a drop is at its minimum. Under experimental conditions this plate temperature was t_W=352°C for kerosene. In the vaporizing element completely different conditions arise, the presence /188 of an air flow, a different means of contact between the fuel and the wall, etc; and therefore the maximum fuel evaporation rate may correspond to other temperature values for the wall.

3. Conclusions

As a result of the investigations experimental data were obtained which characterize the process of fuel evaporation in L-shaped and coaxial vaporizing elements.

The experiments which were conducted demonstrated that the construction of the vaporizing element has a significant effect on the absolute values of the degree of fuel evaporation under given external conditions and on the characteristics of the vaporizing element (the dependence of ϕ on individual factors). Because of this the results of investigations of a vaporizing element of a given construction may not be used directly in developing a combustion chamber with the other type of vaporizing element.

A comparison of the vaporizing elements tested indicates that despite the fact that higher maximum values for the degree of fuel evaporation were obtained with the coaxial vaporizing element, the L-shaped vaporizing element is distinguished by superior characteristics, a smaller change in ϕ with a decrease in α. This is highly significant since, under exploitation condtitions for a combustion chamber, the total air surplus coefficient and, consequently, the air supplus coefficient in the vaporizing element, varies within a wide range.

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