PLANNING OF AN EXPERIMENT TO INVESTIGATE THE EVAPORATION OF A FILM OF HYDROCARBON FUEL

V. N. Afrosimova and E. I. Kozel'skii

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A method and results of a multifactor experiment to investigate the rate of evaporation of a film of fuel in a flow of air are presented.

The problems of the heat exchange and evaporation of films of hydrocarbon fuels have acquired considerable importance at the present time in view of the search to find ways of improving the toxic features of piston and gas-turbine engines by using film mixers.

In the present investigation we experimentally determined the effect of certain operating parameters of the mixing devices on the rate of evaporation of the film of a multifraction hydrocarbon fuel, and we compare the results obtained with theoretical results obtained using an approximate method [1].

The investigation was carried out using the equipment shown schematically in Fig. 1. It consists of a horizontal tube of rectangular cross section mounted in the supercharger line of a compressor. An evaporator element was attached inside the tube flush with the walls; the element consisted of a thin thermally insulated plate (30 × 125 mm), heated by an electric current. At the output end of the plate there was a slit trap to take off the residual (unevaporated) fuel. For visual observations and for photorecording the process a quartz viewing window was fitted to the operating part. The experimental equipment was supplied with pickups to measure the temperature T_a, the flow rate G_a, and the pressure P_a of the air at the entrance to the working part, the electrical heating power of the evaporator plate, and the flow rate of the fuel.

We studied the process in which the fuel is continually supplied to the surface of the heated plate and in which air flows around it in the form of a thin stable film. The layer of fuel exists under conditions of complex heat and mass transfer, when the heat flow is always directed towards the fuel at the wall–film boundary, and at the film–air boundary the heat and mass flows in general have both the same and different directions depending mainly on the temperature of the air. For the basic choice of the geometry of the mixing devices, it is of practical interest to obtain quantitative data on the rate of evaporation of the film when the external heating conditions of the evaporative surface and the flow parameters inside the mixing channel are changed.

The effects of different operating factors (the thermal flux density on the walls q_s, the Reynolds number of the air flow over the film Re_a, the air temperature T_a, and the pressure in the working part P_a) on the rate of evaporation of the film were estimated from the experimental results in agreement with the principles of the mathematical planning of an experiment using the Box–Wilson scheme [2, 3]. The range of variation and the limiting levels of the factors investigated are shown in Table 1. We chose a regular 2^{4-1} semireplica specified by the generating relation $x_4 = x_1x_2x_3$ and defined by the contrast $1 = x_1x_2x_3x_4$ as the experiment planning matrix. To obtain information on the accuracy of the experiment four parallel experiments were carried out at a central point in factor space. In accordance with the randomization principle the sequence of experiments was determined from a table of random numbers.

The order in which each experiment was carried out was as follows. We first set up a certain experiment of a combination of input parameters (q_c, Re_a, T_a, and P_a) specified by the plan, and fuel was then applied to the evaporator plate. The flow of fuel was increased gradually until the first drop of unevaporated fuel began to appear in the measuring vessel of the trap. It was then assumed that the length of the film evaporation path was equal to

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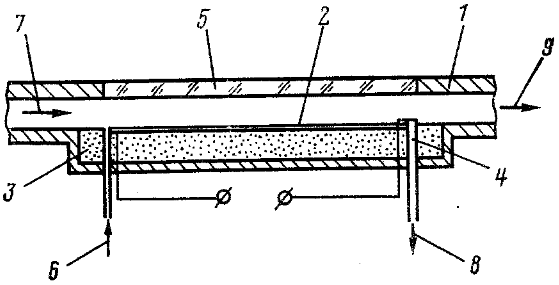

Fig. 1. Sketch of the operating part of the experimental equipment: 1) tube of rectangular cross section; 2) evaporator plate; 3) thermal insulation; 4) trap; 5) viewing window; 6) input of fuel to the plate; 7) air input; 8) extraction of unevaporated fuel; 9) exit of homogeneous fuel—air mixture.

TABLE 1. Levels of the Factors and Variation Intervals

Factor	Code	Level			Variation interval
		lower	basic	upper	
		−1	0	+1	
Heat flux density to the walls q_c, W/m^2	x_1	$5\cdot10^4$	10^5	$1{,}5\cdot10^5$	$5\cdot10^4$
Reynolds number of the air flow Re_a	x_2	$2\cdot10^1$	$6\cdot10^4$	10^5	$4\cdot10^4$
Air temp. T_a, °K	x_3	373	523	673	150
Pressure in the working part P_a, MPa	x_4	0,1	0,3	0,5	0,2

the length of the plate. In addition, the position of the film evaporation boundary was monitored visually, which was easily done because of the dark color of the most volatile tarry fraction of the fuel, which evaporated directly in front of the entrance to the slit of the trap. When the steady thermal state was reached, we measured the flow of fuel and calculated the response function — the rate of evaporation of the film $j = G_f/F_p$, kg/m^2·sec, where F_p is the area of the evaporator plate, m^2.

All the experiments were made using grade DL GOST 4749-73 diesel fuel with temperatures of the beginning and end of the fractional distillation of 180°C and 380°C, respectively. The results of experiments carried out in this matrix are shown in Table 2.

Processing of the results obtained using a typical scheme [2] gave the following regression equation adequately describing the experiment:

$$j = (14.9 + 5.7x_1 + 1.0x_2 + 6.9x_3 - 3.3x_4 + 0.9x_2x_3 - 1.6x_1x_2)10^{-2}. \qquad (1)$$

Comparison of the coefficients of this equation shows that in the chosen region of variation of the input factors an increase in the temperature of the air flow and the degree of heating of the plate had the greatest accelerating effect on the film evaporation. An increase in the pressure in the working region (keeping the other factors constant), on the other hand, leads to some reduction in the rate of evaporation, which can be explained by displacement of the fuel fractional-distillation curve into the higher-temperature region. In this case the amount of heat required to heat the fuel fractions to the equilibrium evaporation temperature increases. In addition, for a fixed value of T_a the increase in the fuel temperature as P_a increases leads to a reduction in the inflow of heat from the air to the free surface of the film due to reduction in the temperature head between the air flow and the fuel layer. If T_a is much lower than the mean temperature of the film, the change in the temperature head as P_a increases brings about an increase in the convective "leakages" of heat into the air from the free surface of the film, thus slowing down the heating and evaporation of the fuel. The relatively small increase in the coefficient with the variable x_2 in Eq. (1) and the significance of the paired interactions x_2x_1 and x_2x_3 indicate that the effect of Re_a (the air flow rate) depends very much on the values of the other factors (T_a and q_c); in particular, the higher the temperature of the air flow the

TABLE 2. Planning Matrix and Experimental Results

No. of expt. in matrix	Random order of carrying out the expts.	Factor								Response function			
			q_c	Re_a	T_a	P_a							
		x_0	x_1	x_2	x_3	x_4	$x_2x_3=x_1x_4$	$x_2x_4=x_1x_3$	$x_2x_1=x_3x_4$	$j\cdot10^2$	$\bar{j}\cdot10^2$	$j_T\cdot10^2$	$\lvert\bar{j}-j_T\rvert\cdot10^2$
01	12		0	0	0	0				11,9			
02	5		0	0	0	0				11,5	12,3	12,2	
03	8		0	0	0	0				12,7			
04	1		0	0	0	0				13,1			
1	11	+	+	+	—	—	—	—	+	14,9	15,5	15,3	0,2
2	7	+	—	—	—	—	+	+	+	4,5	3,9	5,1	1,2
3	6	+	+	—	—	+	+	—	—	11,3	11,9	12,4	0,5
4	4	+	—	+	—	+	—	+	—	1,1	0,5	0,45	0,05
5	10	+	+	+	+	+	+	+	+	25,0	24,4	26,5	2,1
6	9	+	—	—	+	+	—	—	+	8,7	9,3	8,2	1,1
7	3	+	+	—	+	—	—	+	—	31,1	30,5	32,0	1,5
8	2	+	—	+	+	—	+	—	—	22,2	22,8	22,3	0,5
$B_{ci}\cdot10^2=$		14,9	5,7	1,0	6,9	—3,3	0,9	0,6	—1,6				

Note. The spread in reproducibility of the experiments $S^2_{<y>} = 0.53\cdot10^{-4}$, the confidence interval for the response function $\Delta j = 2.3\cdot10^{-2}$, the confidence interval for the regression coefficients $\Delta B_c = 0.82\cdot10^{-2}$, the spread in adequateness $S^2_{ad} = 2.26\cdot10^{-4}$, the Fisher criterion $F = S^2_{ad}/S^2_{<y>} = 4.24 < F_{tab} = 10.1$.

more an increase in Re_a intensifies the evaporation by increasing the heat transfer to the free surface of the film.

Within the framework of the region investigated, Eq.(1) can be used for practical calculations, by changing from coded variables to natural variables:

$$j = -0.172 + 1.62\cdot10^{-6}q_c + 0.25\cdot10^{-8}Re_a + 0.37\cdot10^{-3}T_a - 0.165P_a + 0.15\cdot10^{-8}Re_aT_a - 0.8\cdot10^{-11}Re_aq_c. \quad (2)$$

Table 2 shows values of the rate of evaporation j_f, calculated by the approximate method [1] for the case when q_c = const, and also the values of the disagreements between these values and those calculated from the experimental model (1). As can be seen from these results, the errors in predicting the rate of evaporation from the theoretical relations [1] do not exceed the confidence interval for the experimental resonance function Δj. This enables us to conclude that the proposed calculation scheme satisfactorily takes into account the actual interrelations between the physical processes when a film of multifraction fuel evaporates when there is two-sided heat exchange, and this need not be refined within the limits of the experimental accuracy.

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