THE SETTLING OUT OF IONIZING ADDITIVES FROM A STREAM OF COMBUSTION PRODUCTS

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We examine the settling out of the additives K_2CO_3 and K_2SO_4 from a stream of combustion products onto a laterally streamlined tube. Experimental data are given and the unique features of the process are discussed

Potassium compounds K_2SO_4 and K_2CO_3 are used as ionization additives to the products of combustion in MHD open-cycle generators. Beyond the MHD channel, the additives must be removed from the gas stream. This removal is accomplished in heat exchangers, where the additive is partially settled out on heat-exchanger surfaces, and it is partially converted into an aerosol, which may be trapped with filters [1].

The settling out of the potassium additives was studied in [1, 2]. Tests of a short duration were performed on the settling out of additives onto laterally streamlined tubes and probes, and a detailed study was undertaken of the deposition that occurs on the inside surface of a tube 150 mm in diameter. It developed that the rate of sedimentation formation is less than that given by the theory of mass transfer. This is explained by the formation of an aerosol in the boundary layer. The aerosol is formed on supersaturation of the additive vapors in the boundary layer, near the colder surface.

For a more detailed study of additive deposition on laterally streamlined cooled tubes and to determine the specific features involved in the mechanism, we set up an experimental installation with a combustion chamber [3] that is close in size to the one described in [1]. Figure 1 shows a diagram of the installation. Approximately 10 kg/h of kerosene is burned in air in this chamber (the air flow rate is approximately 170 kg/h). The additive is introduced into the core of the flame in the form of an aqueous solution, through a centrifugal spray nozzle (the solution flows at a rate of 7-10 kg/h). The spray nozzle provides for a very fine atomization, and the droplets are completely vaporized. During the tests, the temperature of the gas flows (after evaporation) registered 1800-1900°K. The evaporating K_2CO_3 and K_2SO_4 additives must, as demonstrated by thermodynamic calculations, decompose in accordance with the following final reactions:

$$K_2CO_3+H_2O\rightleftarrows 2KOH+CO_2, \qquad (1)$$

$$2K_2SO_4+H_2O\rightleftarrows 4KOH+2SO_2+O_2. \qquad (2)$$

In the thermodynamic calculations, the necessary quantities were taken from the data of [2, 4, 5] or they were estimated in tentative fashion. The heat capacities for K_2CO_3, KOH, and K_2SO_4 in the gas phase were calculated with consideration given to the contribution of the rotational and vibrational degrees of freedom, using the formulas cited in [6]. The degree of decomposition for small K_2CO_3 and K_2SO_4 additives (in the order of 0.1% mole and less) at 1800°K is close to unity. With a significant increase in the additive concentration, the decomposition ratio diminishes (particularly for K_2SO_4), and in the case of K_2SO_4 the decomposition ratio is markedly reduced when an excess amount of SO_2 is introduced into the gases.

Thermodynamic calculations also demonstrated that in the case of lower temperatures equilibrium in reactions (1) and (2) on appearance of the condensed phase is shifted in the direction of K_2CO_3 or K_2SO_4 formation. To check this out, we performed tests with KOH added to the gases, or with KOH and SO_2 added

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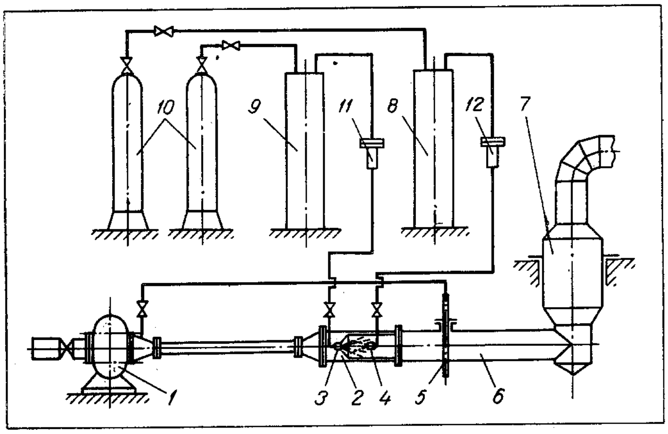

Fig. 1

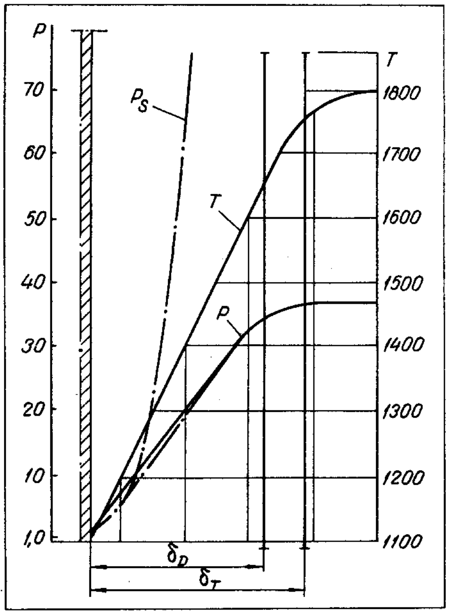

Fig. 2

Fig. 1. Diagram of the experimental installation: 1) gas blower; 2) combustion chamber; 3) fuel spray nozzle; 4) spray nozzle for the additive supply; 5) experimental tube; 6) tube with a diameter of 132 mm; 7) container for the water-jet cleansing of the gas; 8) tank containing additive solution; 9) kerosene tank; 10) compressed air tank; 11,12) filters.

Fig. 2. Diagram of the reduced films at the surface of the experimental tube; T) temperature, °K; P) partial KOH pressure, N/m^2; P_S) equilibrium pressure above the condensed K_2CO_3 phase, N/m^2.

to the gases separately. In the first case, the precipitate consisted of K_2CO_3, as a result of the reaction with the CO_2 in the gases. In the second case, the precipitate consisted virtually entirely of K_2SO_4, despite the substantial excess of CO_2 in the gases. The thermodynamic calculations also show the predominant formation of K_2SO_4 in this case.

When KOH is added to the flow in these tests without SO_2, the KOH concentration in the gases equaled $(1.4\text{-}1.7) \cdot 10^{-4}$ kg/m^3, converted to potassium. The tests lasted about 30-40 min. A tube, 25 mm in diameter and cooled by air from the inside, was streamlined laterally by the gas flow. Metal-covered thermocouples registered the tube-wall temperature at 1000-1100°K (i.e., it was lower than the melting point of K_2CO_3 which is equal approximately to 1170°K). The tube was placed into a cylindrical channel 132 mm in diameter, which served as an extension of the combustion chamber (Fig. 1). The working height of the tube was thus 132 mm. The flow velocity was 22-25 m/sec. The K_2CO_3 precipitate was washed away with water after the test. The amount of K_2CO_3 in the solution was determined by titration with nitric acid of 0.01 normality. After 40 min the K_2CO_3 precipitate weighed 0.8-1.5 g. It should be noted that with the KOH concentrations used in the tests, the tube-wall temperature was higher than the "dew point" for the KOH and KOH condensation was impossible. The condensed K_2CO_3 phase (the aerosol), as per reverse reaction (1), must first be formed. This process must occur in the boundary layer at the tube surface. Figure 2 shows a diagram of the thermal and diffusion reduced films for one of the tests. The thicknesses of the thermal and diffusion films are determined from the relationships [7]

$$\delta_T = \frac{\lambda}{\alpha} = \frac{d}{\mathrm{Nu}}, \quad \delta_D = \frac{D}{\alpha_D} = \frac{d}{\mathrm{Nu}_D}.$$

The diffusion coefficient D for the KOH vapors in the product of combustion was determined approximately in accordance with the Arnold formula [8]. For a temperature of 1800°K and at atmospheric pressure, $D \approx 2.9\ cm^2/sec$. The diffusion coefficient for CO_2 is greater, and the gases contain a substantial excess of CO_2 additives. The KOH diffusion is therefore decisive in the deposition process. The values of the Nusselt numbers Nu and Nu_D are determined by the critical formulas as functions of the Re and Pr numbers (for Nu), or as functions of Re (for Nu_D) [9].

Figure 2 shows the lines characterizing the change in the temperature and partial pressure of the KOH near the tube surface (variation in the magnitudes of the reduced films are assumed to be linear). This figure also shows a plot of the curve giving the equilibrium KOH pressure above the condensed K_2CO_3 phase, which corresponds to the temperature distribution in the reduced film. The equilibrium KOH pressure is assumed to be equal to twice the pressure of the saturated K_2CO_3 vapors.* The latter is found from the Lapeyron–Clausius equation on the basis of tentative values for the heat of evaporation and the boiling point for K_2CO_3.

We see from Fig. 4 that the theoretical KOH pressure in a portion of the reduced film exceeds the equilibrium pressure over the condensed K_2CO_3 phase. Consequently, an aerosol must appear [1, 2, 9], and in this case it must be made up of condensed K_2CO_3 particles. The forming aerosol may settle out on the tube surface under the action of thermophoresis forces [2, 11-13]. A portion of the aerosol may be carried away with the gas flow.

The formulas for the calculation of particle velocity developed as a consequence of thermophoresis are given in [11]. Calculations show that for small particles with a radius substantially smaller than the mean free path of the gas molecules these velocities, in our case, are equal to 6-7 cm/sec. The mean free path of the gas molecules at atmospheric pressure and high temperatures amounts to 0.2-0.4 μm. It is likely that the aerosol particles forming at the tube surface will be smaller in size. Because of the high thermophoresis velocities, a substantial fraction of the particles will reach the surface, since the downwash flow along the tube perimeter will exhibit low velocities (near the surface). As they settle out on the surface, small aerosol particles coagulate as a result of adhesion forces and they take up. As a result, the particles covering the surface are quite large. The precipitate was thicker and denser at the forward end of the tube in these tests, and it was thinner at the trailing end.

The rate of precipitate formation depends on numerous factors. The rate of aerosol particle formation is significant. With a small zone in which the pressure is greater than the equilibrium pressure, aerosol formation may not achieve completion, and under the conditions of these tests the direct condensation of KOH at the tube surface, as was pointed out earlier, cannot take place. The precipitate will then be smaller than it might have been with complete conversion of KOH into K_2CO_3. On the other hand, with a small zone of aerosol formation the aerosol particles will appear near the surface and will settle out well as a consequence of the thermophoresis forces. If the zone of aerosol formation is very thick, the complete conversion of KOH into K_2CO_3 is likely; however, most of the aerosol may be carried away with the flow. It is also essential that in the formation of the aerosol the pressure profile for the KOH in the reduced film becomes steeper (because of the KOH runoff), as shown by the dashed line in Fig. 2. This should lead to an increase in the flow of KOH vapors entering the reduced film. For all of these reasons, the calculation of precipitation on the basis of the formulas for diffusion mass transfer is in need of correction. To do these tests with KOH fed into the flow, we found that the precipitate is smaller than that calculated on the basis of diffusion mass transfer (by a factor of approximately 1.9).

The installation was also used to perform tests on the deposition of K_2SO_4 on a tube (we used the same tube as in previous tests). KOH and SO_2 were fed into the flow separately, or K_2SO_4 was let in at once. The concentration of the additives, converted to potassium, amounted to $(0.2\text{-}0.5)\cdot 10^{-4}$ kg/m^3 in the first case and up to $2\cdot 10^{-4}$ kg/m^3 in the second case. The precipitate was made up of K_2SO_4; in certain cases, the precipitate also contained K_2CO_3 (up to 1%). The tests with separate influx of KOH and SO_2, and the tests with a supply of K_2SO_4, led to comparable results. With a potassium content of $(0.3\text{-}0.5)\cdot 10^{-4}$ kg/m^3 in the flow, the flow velocity was 22-25 m/sec, the flow temperature was 1800°K, and the K_2SO_4 precipitate on the tube amounted to ~0.7-1.2 g within 30 min of operation. The theoretical values for the precipitate in the case of KOH diffusion are of the same order of magnitude.† Thus, in the given case, the K_2SO_4 aerosol is formed intensively at the tube surface; this aerosol is precipitated onto the tube primarily as a consequence of thermophoresis. As was stated earlier, on formation of the aerosol there is an increase in the KOH vapor flow entering the reduced film (the boundary layer). However, this increase in the flow in the tests is apparently offset by the partial entrainment of the aerosol.

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*The pressure of the saturated vapors is doubled as the K_2CO_3 changes into KOH, since two moles of KOH are formed in this case from a single mole of K_2CO_3.

†Generally speaking, the theoretical precipitate is somewhat lower than the experimental. This can be explained, perhaps, by the tentative nature of the theoretical value used for the KOH diffusion factor in the gases, as well as by the effect of the elevated flow turbulence as a consequence of combustion and twisting. This effect had not been taken into consideration in the critical formula utilized in the calculations.

In all cases (whether in the precipitation of K_2CO_3 or in the precipitation of K_2SO_4) the rate of precipitate formation is rather high. Consideration must be given to the possibility of intensive pile-up on the heat-exchanger surfaces in MHD open-cycle generators. As the flow is cooled, an aerosol will be formed in the flow itself. This aerosol must be trapped by filters.

NOTATION

δ_T and δ_D	are the thicknesses of the thermal and diffusion films;
α	is the heat-transfer coefficient;
λ	is the coefficient of thermal conductivity for the gases;
Nu	is the thermal Nusselt number;
d	is the tube diameter;
α_D	is the coefficient of diffusion transfer;
D	is the coefficient of KOH diffusion in the products of combustion;
Nu_D	is the diffusion Nusselt number;
Re	is the Reynolds number;
Pr and Pr_D	are the thermal and diffusion Prandtl numbers.

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