EXPERIMENTAL INVESTIGATION OF THE FILM CONDENSATION OF SULFUR HEXAFLUORIDE ON A FINNED OVERHEAD SURFACE

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The results of investigating the film condensation of sulfur hexafluoride on a finned overhead surface are presented. An experimental apparatus with controlled heat removal is described. The negative influence of noncondensing impurities in the condensible gas and subcooling of the condensation surface on the rate of the process is demonstrated. Methods of eliminating these effects are considered.

Sulfur hexafluoride is widely used as a gaseous dielectric in high-voltage apparatus. However, its insulating properties, especially over an extended period of use, depend to a considerable extent on its content of moisture, oxygen, oils, and other impurities. The permissible impurity content of sulfur hexafluoride is regulated by IEC standard No. 376. These limitations mean that the systems used for filling high-voltage apparatus with SF_6 and evacuating the gas must meet strict requirements. Since as yet there are no factory-made mechanical systems available for evacuating SF_6, attention has turned to the cryogenic pumping method widely used for handling expensive gases. The chief advantages of this method are: high performance, ease of manufacture, low metal consumption, and simple maintenance.

For sulfur hexafluoride, which has a triple point with the parameters p = 0.21 MPa, T = 222°K, in the case of apparatus with a working pressure of from 0.5-0.7 MPa to 0.013 MPa cryogenic recovery involves a two-stage process. In the first stage up to a pressure of 0.25-0.3 MPa in the cryopump chamber sulfur hexafluoride condenses in the liquid phase on the liquid-nitrogen cooled panels, while in the second stage – below 0.25 MPa – the process is one of desublimation. In the future, assuming the use of vacuum-compressors that do not contaminate the gas, it may be possible to condense the sulfur hexafluoride recovered from high-voltage apparatus entirely in the liquid phase using freon refrigerating equipment.

Condensation is a process quite widely used in heat engineering. In most cases mixtures whose components have different phase transition temperatures are condensed. The need to increase the condensation surface while reducing the size of the condensers has led to the development of finned and ribbed surfaces and methods of calculating the optimum geometry of the fins and ribs.

Our purpose was to investigate experimentally the film condensation of impure sulfur hexafluoride on a finned overhead surface in order to determine the main factors that interfere with the normal evolution of the process.

There have been previous experimental investigations of the condensation of multicomponent mixtures by other authors. In [1] it was noted that the process of evacuation of air from an enclosed space ceases long before the pressure reaches a value equal to the resultant partial pressure of the principal noncondensing components of the air at the temperature of the condensation surface. The reason for this was the accumulation of noncondensing gases at the condensation surface, which led to a fall in the partial pressure of the condensed substance and hence to a fall in the temperature of its saturated vapor to the temperature of the surface.

In [2] the investigations concerned the effect of removing noncondensing gas from the surface on the condensation rate of a vapor–air mixture relative to the amount of air and the mixture pressure when a fan-shaped water veil is used as the condensation surface. The high efficiency of air removal, which was accompanied by an increase in the heat transfer coefficient by a factor of 1.5-2, was demonstrated.

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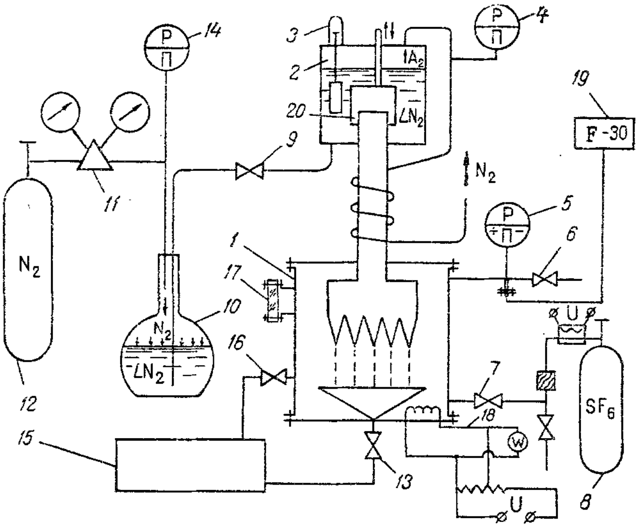

Fig. 1. Diagram of the experimental apparatus.

In [3] the dependence of film condensation on a vertical cylinder on the ratio of the molecular weights of the noncondensing M_n and condensible M_c components of a gas mixture was studied for top and bottom mixture supply. It was found that when the mixture was supplied from the bottom the separation of vapor and noncondensing gas was most fully achieved when $M_c > M_n$ and when the mixture was supplied from the top when $M_c < M_n$. It was established that the heat transfer coefficient increases with increase in the difference between the molecular weights of the vapor and the noncondensing gas.

The condensation rate is known to be proportional to the difference between the temperature of the saturated vapor of the condensible substances and the temperature of the surface. However, an excessive reduction in the temperature of the condensation surface results in the formation of a solid condensate whose low thermal conductivity nullifies the increase in the temperature difference. One of the principal conditions of formation of a solid condensate is, in our opinion, a fall in surface temperature below the triple point of the substance condensed.

The effects accompanying the condensation of a multicomponent mixture noted in [1-3] were taken into account in developing the experimental apparatus for investigating the film condensation of sulfur hexafluoride (Fig. 1).

Sulfur hexafluoride is a convenient substance to investigate since it is chemically inert, nontoxic, and has a higher molecular weight than most of its known impurities.

The composition of the impurities in the SF_6 was analytically determined by a mass spectrometric technique [4] using Soviet MI-1305, MKh-1303 and MKh-1320 instruments and with the assistance of G. V. Karachevtsev and A. Z. Marutkin of the Moscow Physicotechnical Institute.

The design of the condenser is illustrated in Fig. 1, which shows the experimental setup in schematic form. The condensation surface took the shape of a flat horizontal overhead surface with vertical fins of trapezoidal section. It was located in the upper half of the condenser chamber 1. Channels were provided between the fins of the condensation panel to remove the noncondensing impurities. The noncondensing impurities were bled into the atmosphere through a valved outlet 6 at the top of the chamber. Sulfur hexafluoride was supplied from a cylinder 8 through a vaporizer and valve 7 into the bottom of the condenser chamber. The process was observed through a viewing port 17.

The heat flux from the condensation panel was removed through a copper rod, 50 mm in diameter, first to a coil heat-exchanger section filled with nitrogen vapor and then to a section containing liquid nitrogen. This sequence not only ensured efficient utilization of the enthalpy of the liquid nitrogen but also, to a considerable extent, excluded subcooling of the condensation surface. The amount of heat transferred to the coolant was regulated by varying the surface area of the copper rod bathed in liquid nitrogen as a result of vertically displacing the cap 20.

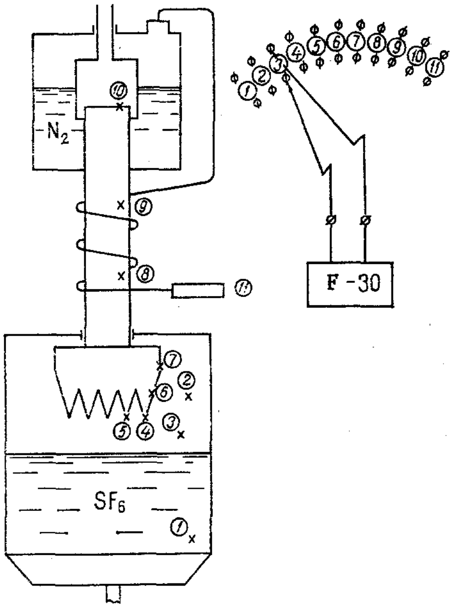

Fig. 2. Distribution of thermocouples.

Before starting the experiments, through valve 6 we evacuated the inner chamber and determined the airtightness from the rate of inleakage, with the object of eliminating the latter. A leakage of 10^{-4}-10^{-5} l/sec was considered acceptable. Valves 7, 13, and 16, open during evacuation, were closed after testing for airtightness. During condensation liquid nitrogen was forced into the nitrogen chamber 2 from a dewar 10 by the overpressure of gaseous nitrogen supplied from cylinder 12 through reducing valve 11. The nitrogen displacement pressure was checked from the readings of manometer 14, the nitrogen vapor pressure in chamber 2 from the readings of manometer 4, the supply of liquid nitrogen being regulated by means of valve 9.

Depending on the test program, gaseous SF_6 was fed into the condenser from cylinder 8 before or after the liquid nitrogen was supplied to the nitrogen chamber. The SF_6 supply line incorporated a dust filter with a dehumidifier. In the initial stage 5-6 kgf of liquid SF_6 accumulated in the condenser.

The nitrogen level in the nitrogen chamber was monitored with a float level gage 3 and maintained so as to ensure that all the heat transfer surface free of cap 20 was in contact with liquid nitrogen.

The temperatures were measured with copper—constantan thermocouples and a F-30 digital millivoltmeter 19. The measured temperature range embraces a zone of variation of thermocouple sensitivity extending from 40 mV/K at room temperature to 17 mV/K at 90°K. For making the thermocouples we used 0.28 mm constantan wire and copper wire of the same diameter. The "hot" junction of the thermocouples was placed in a vessel containing melting ice. According to the calibration data the standard deviation of the readings was 3% at a temperature of 193.6°K and 0.16% at a temperature of 77°K. The location of the thermocouple junctions is shown in Fig. 2.

The experiments began with the supply of power to the heating element (HE) at the bottom of the condenser in the liquid SF_6. The power supplied to the HE was monitored by means of a wattmeter and controlled by circuit 18 across a laboratory transformer. In these experiments the condensate collector 15 was cut off by valves 16 and 13. The mass rate of condensation was determined from the heat output of the heating element divided by the heat of phase transition of SF_6 at the steady-state pressure in the condenser chamber as registered by vacuum manometer 5. Vapor samples were withdrawn through valve 6, and liquid samples through valve 13 with an auxiliary connection. The gas sample volume was 50-100 cm^3. During sampling the sampler was blown through with the sampled gas.

Liquid nitrogen was supplied continuously to avoid disturbing the condensation regime. The temperatures and pressures were recorded at 6 minute intervals. At all the control points the readings of the temperature transducers were recorded under steady-state conditions, i.e., 35-40 min after the onset of each new regime.

TABLE 1. CO_2 Impurity Content of Vapor and Liquid Samples Taken during the Condensation of Sulfur Hexafluoride

State of SF_6	CO_2 content, % by vol.	Condensation characteristic
Vapor	0,028	Crystals on fins
Liquid	0,040	
Vapor	0,077	No crystals
Liquid	0,064	

TABLE 2. Degree of Utilization of Nitrogen Vapor Enthalpy in Liquid-Nitrogen Heat-Exchanger (Φ parameter) as a Function of Sulfur Hexafluoride Condensation Pressure

p, MPa	N, W	Φ
0,29	350	0,27
0,32	400	0,32
0,44	450	0,46
0,58	500	0,47
0,80	550	0,44
1,20	600	0,60
1,49	650	0,55

TABLE 3. Experimental Results of Varying Area of Heat Transfer Surface in Liquid-Nitrogen Heat-Exchanger

N, W	p, MPa	Heat-transfer surface, %
300	0,23	100
	0,45	50
	0,75	25

The experiments were carried out on unpurified (technical) sulfur hexafluoride containing as noncondensing impurities: nitrogen, oxygen, carbon tetrafluoride and carbon dioxide. The interference associated with subcooling of the condensation surface and the buildup of noncondensing impurities was investigated.

In all the cases studied, deviations from the steady-state SF_6 condensation regimes led to a decrease in condenser output. The three most characteristic causes of such deviations were observed to be: 1) buildup of noncondensing impurities at the top of the condenser; 2) subcooling of the condensation surface; 3) appearance of solid-phase deposits on the condensation surface.

The first of these factors is associated with the presence in unpurified SF_6 of the above-mentioned noncondensing impurities. During the condensation process they accumulate at the top of the chamber and block the access of the SF_6 to the condensation surface. This is a well known effect. A reliable method of eliminating it is to dump vapor from the top of the condenser. For technical SF_6 and the experimental apparatus described this operation gave good results.

The second factor, subcooling of the condenser fins, is more specific, since SF_6 has a high triple point at 0.21 MPa and low solid-phase thermal conductivity, namely 0.1-0.2 W/(m·deg) [4]. In the experiments, on a condensation surface at a temperature below 220°K we repeatedly observed the formation of SF_6 crystals, which, after the pressure and temperature in the condensation chamber were raised, remained for 20-40 min from their appearance to their disappearance. The crystalline SF_6 on the condensation surface was a clear glassy film 2-3 mm thick, which repeated the geometry of the condensation surface. In this case film condensation continued to take place on the crystal surface, but at a much lower rate.

During the condensation of SF_6 with a high carbon dioxide impurity content of more than 0.06% by vol., in the absence of subcooling of the condensation surface the appearance on the fin of a "rash" of small individual crystals up to 1 mm in size was observed. The crystals increased in number until the surface of the fin was continuously covered by a hummocky opaque coating. The rate of the process fell. Bleeding vapor from the top of the condenser did not intensify the process or cause the coating to disappear.

The formation of solid phase of this type was observed at pressures of 0.5 and 0.39 MPa, and its disappearance at pressures below 0.29 and above 0.56 MPa.

The impurity composition of samples taken from the vapor and the liquid in the condenser in these experiments showed that the formation of solid phase of this kind on the surface is accompanied by a decrease in the CO_2 content of the vapor and the condensate. Quantitative details are given in Table 1.

"Slush ice" formations associated with the crystallization of SF_6 gas were previously observed in [4]. In the composition of the "slush ice," apart from other impurities, carbon dioxide was present in amounts found to be one order higher than usual. Detailed measurements gave a value of 0.2% by vol., which is consistent with the data obtained in the present investigation.

The appearance of crystals on the condensation surface may be associated with the formation of compounds of the clathrate type with a raised CO_2 content.

On the basis of the results of our experimental investigation of the film condensation of sulfur hexafluoride on a finned surface it is possible to identify the following causes of interference with the normal flow of the process: 1) presence of nonconducting impurities; 2) subcooling of the condensation surface; 3) accumulation of carbon dioxide impurity.

Apart from determining the factors responsible for disturbing condensation, we also experimentally investigated the efficiency of coolant enthalpy utilization and determined the dependence of the SF_6 condensation pressure on the heat-transfer surface in the liquid-nitrogen heat-exchanger.

By varying the heat output of the HE with a fully raised insulating cap, from the temperature of the nitrogen vapor at the coil inlet and the coil outlet we calculated the parameter Φ using the expression

$$\Phi = \frac{c_p(T_{\text{out}} - T_{\text{in}})}{r}.$$

In Table 2 we have reproduced the results, which indicate stabilization of the degree of utilization of the coolant enthalpy (Φ parameter) on the range of condensation pressures p from 0.44 to 1.49 MPa, which corresponds to 50% of the vaporization enthalpy of the liquid nitrogen.

Table 3 gives the relation between the SF_6 condensation pressure and the heat transfer surface in the liquid-nitrogen heat-exchanger for a heater power of 300 W.

The experimental material presented illustrates the heat transfer characteristics of the condenser model investigated.

NOTATION

p, condensation pressure; T_{in}, temperature of the nitrogen vapor at the inlet to the coil heat-exchanger; T_{out}, temperature of the nitrogen vapor at the outlet from the coil heat-exchanger; c_p, specific heat of the nitrogen vapor at constant pressure; r, latent heat of vaporization of liquid nitrogen; N, power output of the heating element.

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INVESTIGATION OF CHEMICAL NUCLEATE BOILING

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The effect of the solution viscosity and particle size on chemical boiling kinetics is established. A quantitative estimate is obtained for chemical nucleate boiling under conditions of free convection.

By chemical boiling we understand the heterogeneous diffusion processes taking place between a solid and a liquid reactant, accompanied by gas release. The investigated reactions between acids, on the one hand, and calcite, magnesium, malachite, and manganese, on the other, take place in the diffusion regime, as confirmed by a series of studies [1-4]. In these processes it is possible to distinguish a region in which the mass transfer coefficient increases with the driving force (reactant concentration). By analogy with boiling heat transfer, it is called the region of the nucleate boiling regime. The kinetics of chemical boiling under conditions of free convection were examined in [5], where the experimental results were quantitatively generalized in the form of criterial relations. The particle diameter, normally used for analyzing mass transfer processes with a dispersed phase, was taken as the linear dimension.

It should be noted that in the experimental results analyzed the diameter of the prepared spherical particles varied only slightly and was equal to 20 ± 3 mm. The diffusion Prandtl number also varied only slightly and accordingly we used the relation

$$\mathrm{Nu} \sim \sqrt[3]{\mathrm{Pr}}, \tag{1}$$

which has been recommended for mass transfer processes by a number of authors, for example in [6].

As shown by the experimental data on boiling heat transfer, in the region of developed nucleate boiling the heat transfer rate is unaffected by the Prandtl number and the geometric dimension [7]. It therefore became necessary to probe more deeply into the effect of certain parameters on the chemical boiling kinetics.

Above all, it is a question of establishing the dependence of the mass transfer coefficient on the particle diameter and the viscosity of the solution as they vary over a fairly wide range. We began by preparing spherical particles of different sizes which were subsequently immersed in a reactant solution with a given concentration and temperature. From the weight loss of the particle ΔM on a certain experimental time interval τ we found the mass transfer coefficient

$$k_R = \frac{\Delta M}{nFc_R\tau}. \tag{2}$$

It is clear from Fig. 1 that in the region of the nucleate boiling regime on the particle diameter interval 7.5-25 mm the quantity k_R is self-similar relative to the dimension of the solid phase. As the linear dimension it is convenient to use the linear scale of capillary-gravitational interaction ℓ^* [7]:

$$l^* = \left[\frac{\sigma}{g(\rho' - \rho'')}\right]^{1/2}. \tag{3}$$

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