CONDENSATION OF CESIUM VAPOR FROM FLOWING ARGON

V. M. Borishanskii, I. I. Paleev,*
K. M. Aref'ev, N. I. Ivashchenko,
T. V. Zablotskaya, B. M. Khomchenkov,
and N. M. Fishman

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This article considers experimental data on the condensation of small amounts of cesium from flowing argon. We have analyzed the influence of mist formation on condensation and compared the experimental data with calculated results.

It has been suggested that cesium be used as an ionizing additive in MHD generators of the closed-system type operating with inert gases. The cesium should be removed from the gas stream beyond the MHD channel. Partial removal can be obtained by condensation of the cesium on cooled heat-exchanger surfaces.

The amount of cesium in the inert gas is small, less than 0.1 mole %. The condensation of such small amounts results from diffusion of vapor through the gaseous boundary layer to the cooled surface [1]. In making calculations, it is possible to utilize the analogy between heat and mass transfer; the restrictions associated with the influence of Stefan flow are unimportant at small cesium concentrations. However, mist formation can have some effect [2]. During cooling of the gas in the stream and in the boundary layer, the vapor can become supersaturated as a result of the large reduction in saturation pressure with decreasing temperature. Homogeneous (volumetric) condensation, or mist formation, then begins. When the gas has a normal content of foreign condensation centers (dust particles, etc.), volumetric condensation begins at a low degree of supersaturation $p/p_s = 1.02\text{-}1.12$ [2].

The present investigation was undertaken to study the condensation of cesium from a flowing inert gas (argon) under conditions where mist formation can occur. The first series of experiments in which we studied the influence of mist formation was conducted in stainless steel tubes with inside diameters of 4.5 and 1 mm and a wall thickness of 0.2 mm. The tube length was 300 mm. In the experiments, argon with a cesium content of from $1.1 \cdot 10^{-4}$ kg/kg to $10 \cdot 10^{-4}$ kg/kg (the cesium was preliminary vaporized from a special container) was supplied to the tube. The temperature of the argon at the tube inlet was 723°K, while that at the tube outlet was virtually identical to the tube-wall temperature. The tube was placed in a glycerine bath, whose temperature (and hence the tube-wall temperature) was varied from 285 to 433°K. The flow speed in the tube (at the average gas temperature) ranged from 1.5 to 65 m/sec, while the Reynolds number ranged from 160 to 1550 (the flow regime was laminar or of the transition type). The argon from the tube outlet was delivered to absorbers, where it was bubbled through nitric acid solution. The cesium was chemically bound. The final cesium concentration in the argon at the tube outlet was determined from chemical analysis of the solution after a known amount of argon was passed through it. The cesium that accumulated on the tube walls was washed off with water after the experiment. The amount of condensed argon was determined from chemical analysis of the solution. We also knew (from the weight loss of the evaporatory beaker) the amount of cesium entering with the incoming argon stream. The cesium balance was accurate to within 0.5%.

* Deceased.

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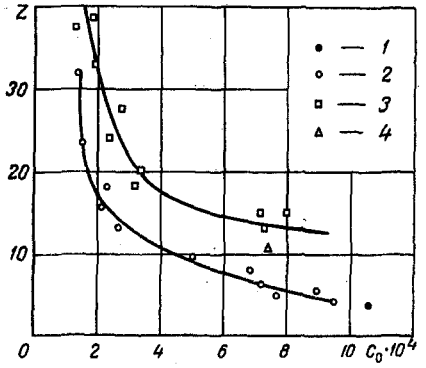

Fig. 1

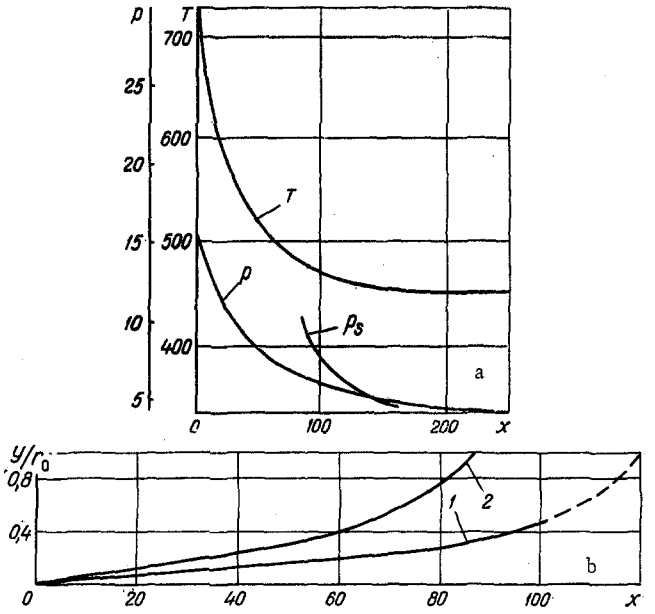

Fig. 2

Fig. 1. Relative cesium deposition Z (%) in tube as a function of incoming cesium concentration C_0 (kg/kg). Argon delivery of $2.1 \cdot 10^{-5}$ kg/sec, flow speed of ~1.5 m/sec. The average curve corresponds to a wall temperature of 403-433°K (top line) or 373°K (bottom line). The experimental points correspond to the following wall temperatures: 1) 285; 2) 373; 3) 403-433; 4) 473°K.

Fig. 2. Distribution of gas temperature T (°K), partial cesium pressure p (N/m^2), and cesium saturation pressure p_S (N/m^2) over tube length x (mm) (a) and mist-formation boundary region near tube wall (b): 1) $C_0 = 10^{-4}$ kg/kg; 2) $C_0 = 5 \cdot 10^{-4}$ kg/kg; argon delivery rate of $2.1 \cdot 10^{-5}$ kg/sec, flow speed of ~1.5 m/sec.

Figure 1 shows the results of some experiments, in the form of the dependence of the relative cesium deposition Z on the incoming cesium concentration C_0 and the wall temperature T_{wa}. It can be seen that the relative deposition decreased as the cesium concentration C_0 increased. The deposition was less at low wall temperatures (285 and 373°K) than at higher temperatures (403 and 433°K). The deposition again became smaller at temperatures above 473°K.

The dependence of the relative cesium deposition on the incoming concentration and wall temperature can be explained by the influence of mist formation. When the inlet concentration (partial cesium pressure) was increased, mist formation began closer to the tube inlet (Fig. 2a). This resulted in a decrease in relative deposition ahead of the mist-formation zone:

$$Z = \frac{p_0 - p^*}{p_0}, \qquad (1)$$

where p* is the partial pressure corresponding to the intersection point of the p and p_S curves. The mist droplets were removed by the stream and almost none of them were deposited on the walls under our experimental conditions. We conducted a control experiment with a coiled tube 2 m long. A large increase in tube length did not lead to an increase in deposition.

Mist developed not only in the heart of the stream but also in the boundary layer at the wall. Figure 2b shows the calculated boundaries of the zone of cesium-vapor supersaturation at the tube wall for one regime (two incoming cesium concentrations). As can be seen, the region in which mist formation was possible began close to the inlet. The thickness of this region was initially small and deposition on the walls was possible; the zone thickness then increased and the zone ultimately covered the entire flow cross section. As the cesium concentration increased, the mist-formation zone became thicker and covered the flow cross section earlier. As the wall temperature decreased, the thickness of the mist-formation zone increased and the cesium deposition decreased. Conversely, as the wall temperature rose, the mist-formation zone became thinner and mist developed later in the interior of the flow. This promoted an increase

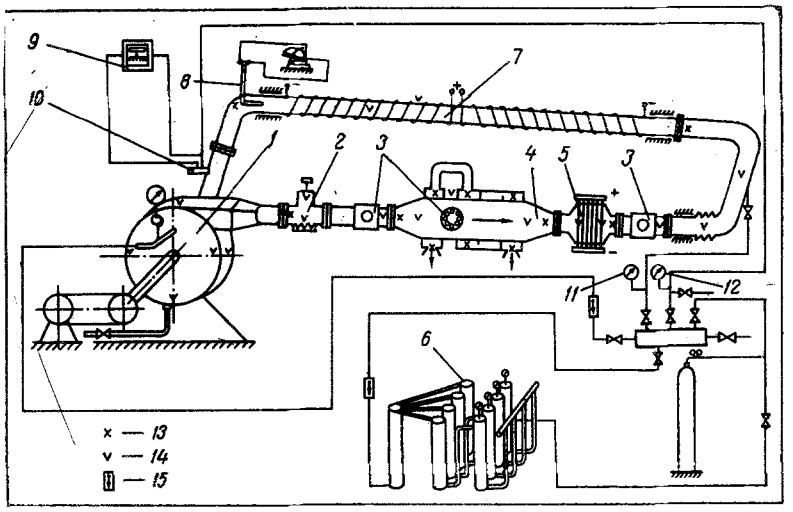

Fig. 3. Diagram of experimental apparatus for studying condensation of cesium in tube bundle. 1) Gas blower; 2) evaporation unit; 3) plugs; 4) working portion; 5) heating element; 6) gas purification unit; 7) heating element; 8) high-speed tube; 9) reference gage; 10) pressure sensor; 11) manometer–vacuum gage; 12) specimen manometer; 13) main thermocouples; 14) control thermocouples; 15) gas flow-speed meter.

in deposition. However, there was a decrease in the difference in the partial cesium pressures in the stream and at the wall (at the surface of the condensate film) as the wall temperature rose. The partial cesium pressure at the wall equaled the saturation pressure at the wall temperature, increasing with rising wall temperature. The cesium deposition eventually began to decrease at elevated wall temperatures. The temperature at which this occurred was 400-430°K under our experimental conditions. Theoretical calculations yielded the same results.

The cesium deposition was markedly increased as a result of mist formation at the wall. Calculation of the cesium condensation by analogy with heat transfer during laminar flow in a tube yielded results that were too high if one took into account only the mist formation in the stream itself and not that of the mist formation at the wall. As the Reynolds number increased and particularly on moving to a turbulent flow regime, the negative influence of mist formation at the wall should become weaker as a result of the decrease in boundary-layer thickness. Confirmation of this is provided by the results of a study [3] of the condensation of potassium and cesium from flowing argon in a tube with Reynolds numbers of up to 11,500.

Our second major series of experiments was conducted with a tube bundle with lateral flow-by. Figure 3 is a diagram of the apparatus. The argon was pumped through a closed system from a stainless steel centrifugal gas blower. The argon was heated before the blower with electric heating elements to 543-623°K. The blower itself was also heated. The cesium was introduced into the argon beyond the blower by vaporization from a special beaker. The working section of the apparatus consisted of a bundle of tubes 12 mm in diameter arranged in checkerboard fashion, with lateral flow-by. The relative spacing across the front of the bundle was 2 (with five tubes per row and a tube height of 140 mm), while that from front to back was 1.5. The bundle consisted of two individual sections connected in series. The first section (in the argon flow path) contained eight rows of tubes, the second containing 24 rows (in three gangs of eight rows each). The working length of the bundle was 560 mm.

The tubes in the bundle were air-cooled from inside. The air, supplied by a special blower, was successively delivered to the three sections of the second portion of the bundle (from the argon-outlet side) and then to the first portion. The argon flow rate through the bundle was from 0.028 to 0.067 kg/sec with a velocity (at the narrowest point) of from 3 to 8 m/sec; the Reynolds number ranged from 1200 to 3000 over the tube diameter. The argon temperature at the bundle inlet was 543-623°K, while the outlet temperature was 353-403°K.

The cesium concentrations in the argon ahead of and beyond the bundle were determined by chemical analysis of gas samples. For sampling, the gas was bubbled through nitric (or sulfuric) acid solution and

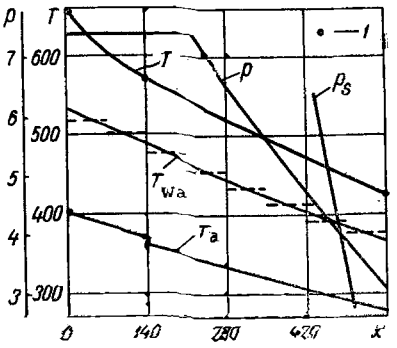

Fig. 4

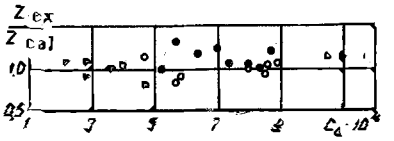

Fig. 5

Fig. 4. Calculated curves for change in temperature (°K) of argon T, air T_a, and wall T_{wa}, partial cesium-vapor pressure p (N/m^2), and cesium-vapor saturation pressure p_S (N/m^2) over length of bundle x (mm) for one experiment. 1) Experimental points. Argon flow rate of 0.045 kg/sec, incoming cesium concentration $C_0 = 2.3 \cdot 10^{-4}$ kg/kg, and $Z_{cal} = Z_{ex} = 43\%$.

Fig. 5. Ratio of experimental (Z_{ex}) and calculated (Z_{cal}) cesium deposition at different C_0 (kg/kg).

the gas flow rate measured. The cesium concentration at the bundle inlet ranged from $2 \cdot 10^{-4}$ to $11 \cdot 10^{-4}$ kg/kg. In most of the experiments of the first series, the relative cesium deposition Z in the bundle was 35-45% of the amount of cesium admitted; the figure for the second series (with parallel supply of cooling air to all the bundle tubes) was 50-65%. The deposition was as low as 15% in only one experiment, in which mist formation occurred close to the inlet.

We made a comparison of experimental and calculated data on cesium deposition. The changes in temperature and partial cesium pressure over the length of the bundle were determined from relationships derived from the mass- and heat-transfer equations:

$$T = T_{wa} + (T_0 - T_{wa}) \exp(-kx), \tag{2}$$

$$p = p_{wa} + (p_b - p_{wa}) \exp(-nx). \tag{3}$$

where

$$k = \frac{\mathrm{Nu}}{\mathrm{Pe}} \cdot \frac{F_{ext}}{F_{l.s}} \cdot \frac{1}{L}, \tag{4}$$

$$n = \frac{\mathrm{Nu}_D}{\mathrm{Pe}_D} \cdot \frac{F_{ext}}{F_{l.s}} \cdot \frac{1}{L}. \tag{5}$$

In making the calculations, the bundle was divided into several zones. The wall temperature, determined with the heat exchange with the air inside the tubes taken into account, was assumed to be constant in each zone. The physical constants were calculated for the average gas temperature in the zone. The values of Nu and Nu_D were determined as functions of Pr and Pr_D (for Nu_D) and of the structural characteristics of the bundle, using the formula given by Mochan et al. [4]. The diffusion constant D_n of cesium vapor in argon was taken from the data obtained previously [5].

The calculated results were used to plot curves representing the change in the temperature, partial pressure of the cesium vapor, and saturated vapor pressure along the bundle length. The intersection of the latter two curves defines the start of the mist-formation zone in the stream (Fig. 4). It was assumed that the cesium deposition could be neglected in the mist-formation zone. The relative deposition before the mist-formation zone was determined from Eq. (1). Figure 5 gives the ratio of the experimental and calculated values of Z. This ratio was close to one for most of the experiments.

Mist formation can begin somewhat earlier in the boundary layer at the tube surface than in the interior of the flow. During turbulent flow, however, the influence of the mist formation at the wall on diffusive condensation is very slight and lies within the range of experimental error. Mist droplets formed

in the interior may be partially deposited on the tube walls as the stream flows by them. Deposition of mist droplets or the molecular aggregates that are their predecessors was detected in a study [6] of the condensation of mercury from flowing air in a tube bundle with transverse flow-by.

Our analysis (Fig. 5) has shown that calculations made by the proposed method (without taking into account mist formation in the boundary layer or mist deposition as it flows by the bundle) yield results that are, on the average, correct for our experimental conditions.

NOTATION

p	is the partial cesium-vapor pressure;
p_s	is the pressure of saturated cesium vapor;
Z	is the relative cesium deposition;
T	is the stream temperature;
T_0	is the stream temperature at inlet;
T_{wa}	is the wall temperature;
x	is the coordinate along bundle length;
p_0	is the partial cesium-vapor pressure at inlet;
p_{wa}	is the partial cesium-vapor pressure at wall surface, equal to saturated vapor pressure at wall temperature;
$Nu = \alpha d/\lambda$	is the Nusselt thermal criterion;
α	is the heat-transfer constant;
d	is the tube diameter;
λ	is the coefficient of thermal conductivity of gas;
$Pe = wd/a$	is the Peclet thermal criterion;
w	is the flow speed;
a	is the thermal diffusivity of gas;
F_{ext}	is the external surface area of tubes in bundle;
$F_{l.s}$	is the live cross section of tube;
L	is the total length of bundle in gas path;
$Nu_D = \alpha_D d/D_{12}$	is the Nusselt diffusion number;
α_D	is the diffusive transfer constant;
D_{12}	is the diffusion constant;
$Pe_D = wd/D_{12}$	is the Peclet diffusion number;
$Re = wd/\nu$	is the Reynolds number;
ν	is the kinematic viscosity of gas;
$Pr = \nu/a$	is the thermal Prandtl number;
$Pr_D = \nu/D_{12}$	is the Prandtl diffusion number (Schmidt number).

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