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LABORATORY MODELING OF THE INTERACTION OF VAPOR-AIR PLUMES FROM COOLING TOWERS WITH JETS FROM THE VENTILATION PIPES OF ATOMIC ELECTRIC POWER PLANTS

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We present experimental results obtained with the help of optical methods. We determined the position of the effective source of ejections and the boundaries of the zone of the interaction of streams.

Introduction. In order to apply modern mathematical models that describe in a two-dimensional approximation the propagation of an admixture in the atmosphere [1], it is necessary, in particular, to assign boundary conditions for the concentration and velocity of the admixture on a certain plane A. Usually, the position of the plane A coincides with the source of ejections. However, in some cases the situation is far from being so simple. As shown in [2], the propagation of the radioactive aerosols ejected through the ventilation pipe of an atomic electric power plant (AEPP) is substantially influenced by the capture of the aerosol by the drops [3, 4] of the vapor-air plume from the cooling tower. Thus, in this case the determination of the position of the plane A depends substantially on the process of the mixing of the cooling tower plume with the jet flow from the ventilation pipe (see Fig. 1).

If we introduce a coordinate system (x, y, z) such that the coordinate origin is located at the center of the cooling tower outlet, the x axis is directed windward and the z axis is vertical, the position of the plane A will depend on the following parameters: D, d, L, H, h, u, v, ρ_v, ρ_a (D, d are the diameters of the outlets of the cooling tower and ventilation pipe; u and v are the wind velocity and the vertical velocity of an outgoing vapor-air spray cone). It is natural that the value of v depends on the initial temperature of the circulating water, the temperature and humidity of surrounding air, the height of the cooling tower, and a variety of other parameters. Let us determine the coordinate x_0 of the position of the plane A as half the difference of the coordinates between the points of intersection of the cooling tower plume, jet from the ventilation pipe, and of the end of the plume. Then, as follows from dimensional considerations [5], the coordinate x_0 of the position of the plane A will depend on the following dimensionless groups:

$$x_0 = DF(d/D,\ L/D,\ H/D,\ h/D,\ u/v,\ \rho_a/\rho_v), \tag{1}$$

where F is an unknown dimensionless function.

Taking into account the results of [6, 7] and the fact that $d/D \ll 1$, we rewrite Eq. (1) in the form:

$$x_0 = DF_1(L/D,\ H/D,\ h/D,\ \rho_a u^2/\rho_v v^2), \tag{2}$$

where F_1 is an unknown function of dimensionless arguments.

It is known that $H/D \approx 2$ [8]. Since we neglect the vertical gradients of the wind velocity (which is valid for the heights of the order of hundred meters), only the relative height Δh ($\Delta h = H - h$) is of importance. Thus, we reduce the number of independent arguments in Eq. (2) and obtain

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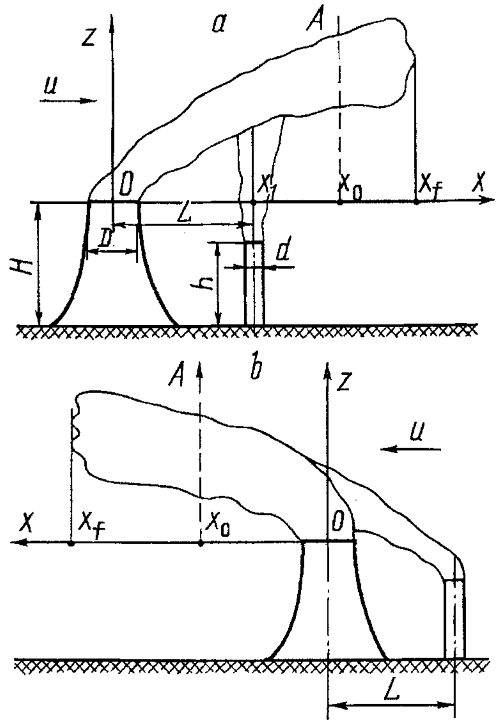

Fig. 1. Scheme of aerodynamic interaction of the cooling tower plume with ejections from a ventilation pipe: a) wind from the side of the cooling tower; b) from the side of the ventilation pipe.

$$x_0 = DF_1\,(L/D\,,\ \ \Delta h/D\,,\ \ \rho_a u^2/\rho_v v^2)\,. \tag{3}$$

It is the determination of the form of the function F_1 from experimental data which is the aim of the present work.

From the viewpoint of the mechanics of continua, we investigate a particular case of the problem about the penetration of two jets into a sweeping stream [9] whose part is played by wind. Since $d/D \ll 1$, the process of mixing is determined in the main by the properties of the cooling tower plume. As shown in [9, 10], the trajectory of the plume axis $z_p(x)$ is rather well described by the equation

$$Z_p/D \approx a\,(x/D)^2\,\rho_v v^2/2\,\rho_a u^2\,. \tag{4}$$

The coefficient $a \simeq 1$ is an adjusted value and must be determined from experimental data. We should note an interesting fact discovered experimentally in [10, 11]: a plane jet covers a distance not more than 20 diameters of the nozzle in the direction of the sweeping stream. In the leeward portion, a rather intense vortex is formed that limits the propagation of the plane jet. A similar mechanism operates also for a round jet [12], to which, with adequate accuracy, can be related a cooling tower plume; thus the vortex influences the value of x_0.

It is useful to estimate the limiting distance l over which the effects of the interaction of wind with the cooling tower will cease to exert effect on the flow from the ventilation pipe. In fact, after the flow around the cooling tower the divergence angle of the turbulent stream is approximately equal to 13^0 [7]. As follows from simple geometric considerations, the stream will converge at the distance

$$l \approx D_1/2\,\tan 13^0 \approx 2.2\,. \tag{5}$$

As follows from [8], $D_1 \approx 2D$. Whence it follows that if $L > 1$, the investigated effect from the interaction of two streams disappears. The above considerations were used for the statement of the problem and processing of experimental results.

ABLE 1. Experimental Data on the Mixing of the Plumes of the Cooling Tower and Ventilation Pipe at $L/D = 2.0$

No. of regime	u, m/sec	x_1/D	x_f/D	No. of regime	u, m/sec	x_1/D	x_f/D
1	0	−0.75	0	5	0	0.75	0
2	0.5	0	4	6	0.5	2	5
3	1	0	4	7	1	2	5
4	2	0	4	8	2	2	5

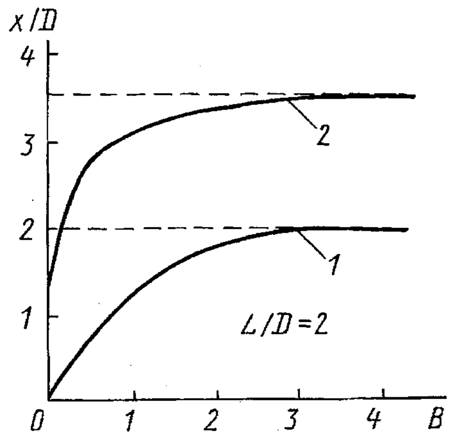

Fig. 2. Dependence of the position of the plane A on the dimensionless complex B: 1) wind from the side of the cooling tower; 2) from the side of the ventilation pipe; direction of wind coincides with the line that connects the cooling tower with the ventilation pipe.

1. Experimental Procedure. Experimental investigations of the interaction of plumes from the cooling tower and ventilation pipe of an AEPP were carried out on a rig whose principal element was an IZK-463 holographic interferometer [13]. A model involving a cooling tower and ventilation pipe was installed on a stand between the collimator and receiving portions of the IZK-463 device. The model could be rotated at various angles to the direction of viewing and to the air flow (wind). The wind was imitated with the help of a small wind tunnel (100 × 270 mm cross section) with an open working section. The flow velocity was regulated by the voltage supplied to the electric motors of fans and was measured by an ASO-3 anemometer, making it possible to record flow velocities of from 0.3 to 5 m/sec.

The experiments were carried out for four regimes governed by wind velocities of 0, 0.5, 1.0, and 2.0 m/sec. In this case the velocity of the vertical stream from the cooling tower v was constant and equal to 1 m/sec. In our experiments the velocity of escape from the ventilation pipe was also constant and equal to 2 m/sec. In other words, the dimensionless group B ($B = \rho_a u^2/\rho_v v^2$) varied within the range from 0 to 4. During the experiment we measured and controlled the following parameters: wind velocity, volumetric gas flow rate from the model involving the cooling tower and ventilation pipe, the ambient air temperature, and the temperature of the gas escaping from the models of the cooling tower and ventilation pipe.

Basic results needed for investigating the process of the interaction of streams were obtained by visualizing the flow with the aid of an IZK-463 holographic interferometer, which was used in the regime of shadowgraph operation. Due to the large field of vision (of about 800 mm in diameter), the interaction of streams was observed at a great distance, up to the complete mixing of jets with the surrounding air. The observed shadow pattern was photographed by a "Salyut-S" camera. In the most interesting cases the process of stream interaction was photographed by a videocamera.

During the subsequent investigation and processing of the shadowgrams, we determined the structure of the flow in the zone of interaction (formation of vortices and of unstable vortical formations) and fixed the

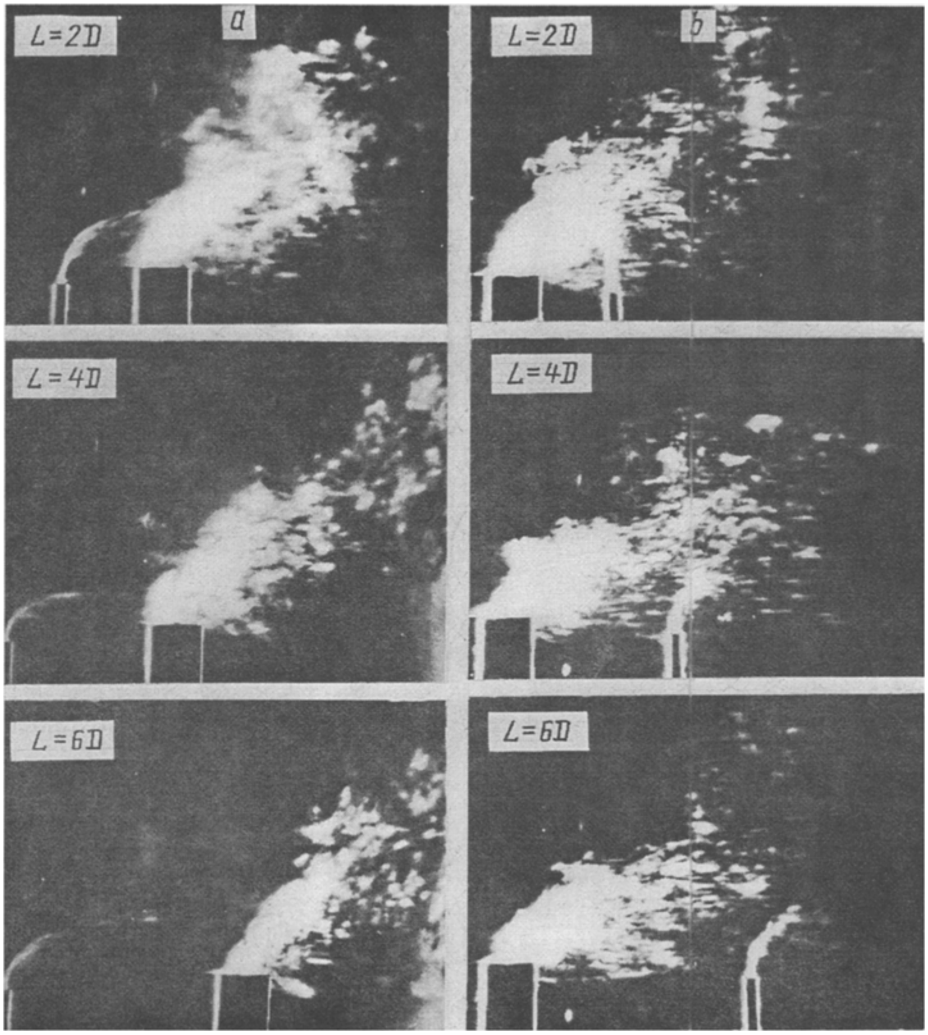

Fig. 3. Shadow photographs of the interaction of the cooling tower plume with the stream from the ventilation pipe on the laboratory model: a) wind from the side of the ventilation pipe; b) from the side of the cooling tower.

coordinates (x_1, z_1) at the start of the zone of the mixing of streams (see Fig. 1) from the cooling tower and ventilation pipe and the end of the plume from the cooling tower (x_f, z_f).

2. Results of Experiments. Table 1 presents data on the location of the model, operational parameters, and positions of the start and end of the zone of mixing made nondimensional through division by the cooling tower diameter D.

In the first version (regimes 1-4) the wind is directed from the ventilation pipe to the cooling tower. At $u = 0$ the interaction follows the laws of mixing of turbulent gas jets [14]. The increase in the wind velocity displaces the coordinate of the start of the zone of mixing to the upper outlet of the cooling tower.

When the wind velocity is directed from the cooling tower (regimes 5-8), the x_1 coordinate virtually coincides with the coordinate of the ventilation pipe. The z_1 coordinate depends on the wind velocity; it decreases with an increase of the latter in close agreement with formula (4). In this case under the conditions of our experiment the coefficient a in formula (4) was equal to 0.75 for regime 1 and $a \approx 0.65$ for regime 2.

The determination of the coordinates for the end of the plume (x_f, z_f) is associated with an error attributable to the adopted procedure of the experiment (conditions of visualization, contrast of the shadow pattern photograph) and by a certain arbitrariness of the concept of "the end of the plume." However, our multiple investigations have shown that the absolute error does not exceed $(0.5-0.75)D$.

The experimentally obtained dependence of the coordinate x_0 on the parameter B from Eq. (3) at $L/D = 2.0$ is given in Fig. 2.

Comparing the results obtained, we can note a rather strong dependence of the values of (x_0, z_0) on the relative position of the cooling tower and ventilation pipe with respect to wind provided that the direction of the wind coincides with the line that connects the axes of the cooling tower and the pipe or close to it (with account for simple geometric relationships between the diameter of the cooling tower L and the direction of the wind). Otherwise, the effect of the interaction of streams is much smaller, and with sufficient accuracy it is possible to use a widely distributed technique of the superposition of flows [5].

In order to elucidate the effect of the distance between the pipe and the cooling tower on the process of mixing, we conducted experiments at different values of the parameter L/D, in particular, at L/D equal to 2, 4, and 6. Shadow photographs of regime 1 ($v = 1$ m/sec) for different values of L are presented in Fig. 3a. It can be easily seen that at $L = 4D$ the effect of the relative location of the pipes decreased significantly, and it is entirely absent for $L = 6D$.

When the ventilation pipe is located behind the cooling tower (Fig. 3b), the effect of wind shadow is observed. When $L > 6D$, the wind shadow effect disappears completely. When $L < 4D$, the x_0 coordinate is fully determined by the propagation of the cooling tower plume, since the stream from the ventilation pipe rises strictly vertically.

The effect of the parameter $\Delta h/D$, which, as follows from Eq. (3), influences the value of x_0, was modeled with the proviso that $\Delta h > 0$. We found that for $L < 4D$ and $0.5 < \Delta h/D < 1$, there is virtually no dependence of x_0 on this parameter. It is evident that the situation will change sharply for $\Delta h < 0$, when the ventilation pipe is higher than the cooling tower. In this case the propability of entrainment of aerosol by the droplets from the cooling tower plume will decrease as the interaction between the two streams becomes weaker.

NOTATION

ρ_v, ρ_a, density of the vapor-air plume of a cooling tower and of the ambient air; L, distance between the axes of the cooling tower and pipe; H, h, height of the cooling tower and ventilation pipe; D_1, height-averaged diameter of the cooling tower.

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