Nomenclature

$\bar{A}$, $\bar{A}_x$, $\bar{A}_y$ - rms amplitudes of tube vibrations in any, longitudinal and transverse directions relative to the direction of an incident flow, m;

a - relative transverse pitch (s_1/d), thermal diffusivity, m^2/s;

b - relative longitudinal pitch (s_2/d);

b' - relative diagonal pitch of the staggered bundle (s_2'/d);

c_D - total drag $(P_D/(0.5dl\rho\bar{u}^2))$;

s_f - friction drag $(P_f/(0.5dl\rho\bar{u}^2))$;

c_w - pressure drag $(P_w/(0.5dl\rho\bar{u}^2))$;

c_x, c_y - coefficients of the longitudinal and transverse nonstationary fluid-dynamic forces $(P_x/(0.5dl\rho\bar{u}_2))$, $(P_y/(0.5dl\rho\bar{u}^2))$;

d - diameter, m;

e - nondimensional displacement of the tubes relative to the symmetric position $(y/(s_1 - d))$;

$\bar{e}$ - relative spacing between the tube bundle and the wall $(h/(s_1 - d))$;

l - tube length, m;

l_c - correlation length, m;

Δl - distance between two measurement points, m;

F - force, N;

f - frequency, Hz;

f_s - frequency of vortex shedding, Hz;

f_n - natural frequency of tube vibrations, Hz;

h - channel height; minimal flow section between the end tube of the bundle and the channel wall, m;

m - design mass of the tube per unit length ($m_t + m_a + m_l$), kg/m;

m_t, m_a, m_l - tube mass, additional fluid mass and fluid mass in the tube, respectively, kg/m;

P_D - resultant drag force ($P_f + P_w$), N;

P_f, P_w - resultant of the frictional forces and resultant of the pressure forces, respectively, N;

P_x, P_y - longitudinal and transverse stationary fluid-dynamic forces, N;

p - pressure, Pa;

Δp - pressure drop, Pa;

$\bar{p}$ - pressure coefficient $(1 - \Delta p/(0.5\rho\bar{u}^2))$;

S_A, S_u - spectral density of the tube vibration amplitude and of the flow velocity fluctuations, respectively, s;

s_1, s_2 - transverse and longitudinal pitches between the bundle tubes, m;

s_2' - diagonal pitch of the staggered tube bundle, m;

Tu - turbulence degree, $\sqrt{\overline{u'^2}}/\bar{u}$

t - time, s;

Δt - time interval, s;

U_0 - velocity of the incident flow, m/s;

$\bar{u}$ - velocity in the narrow cross section of the bundle ($U_0 a/(a-1)$), m/s;

u, v, w - components of the flow velocity, m/s;

u', v', w' - fluctuating components of the flow velocity, m/s;

X, Y - drag and lift forces, respectively, N;

x, y, z - Cartesian coordinates, m;

α - angle of the bundle turn relative to the flow direction, deg.; thermal conductivity, W/(m^{2}K);

β - angle of the tube inclination to the flow direction, deg.;

δ - logarithmic decrement;

μ - dynamic viscosity, Pa·s;

γ - kinematic viscosity m^2/s;

ρ - fluid density, kg/m^3;

σ - stress, N/m^2;

φ - angle, deg.;

ω - angular frequency ($2\pi f$), 1/s;

Pr - Prandtl number (ν/a);

Re - Reynolds number ($\bar{u}d/\gamma$);

Sh - Strouhal number ($f_s d/\bar{u}$);

$\mathbf{Sh_n}$ - nondimensional vibration frequency of the tubes ($fd/\bar{u}$).

Subscripts:

f, 0 - in the undisturbed flow;
w - at the wall;
$(\bar{\ })$ - averaging;
$(\ )'$ - fluctuating components.

The remaining nomenclature is given in the text.