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AN ANOMALOUS CHANGE IN THE SUPERCOOLING OF VAPOR IN SPONTANEOUS CONDENSATION

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Spontaneous condensation of vapor at transonic velocities in the subsonic part of a flow in contrast to condensation in all the remaining regions of the flow leads not to an increase, but rather to a decrease in temperature and not to a drop, but rather to a rise in the supercooling of vapor.

As is known [1, 2], the expansion of high-velocity vapor flows in the region of phase transitions occurs with substantial deviations from thermodynamic equilibrium that are responsible for a number of special features of flow in the zone of initial condensation. Among these, the main ones are:

(a) the gradual accumulation of deep supercooling $\Delta T = T - T_s$ required for spontaneous formation of a rather large number ΔN of condensation nuclei, whose relative mass is Δy_l;

(b) the explosive character of the initial moisture formation, when in a very small interval of time $\Delta\tau$ over a short portion of the flow an amount Δy of vapor goes into the liquid phase and this is accompanied by local liberation of the heat $\Delta q = r\Delta y$ into the flow and (except for the cases considered below) by a sharp decrease in supercooling virtually to zero;

(c) conservation of relatively small values of supercooling ΔT on further expansion and actual termination of the formation of new condensation nuclei (except for the virtually nonoccurring cases of extremely sharp further expansion of the flow);

(d) local (in the zone of spontaneous condensation) retardation of a supersonic flow ("condensation jump") or acceleration of a subsonic flow ("condensation wave"), whose intensity is determined by the relationship between the gradients of flow expansion $\Delta F = (1/F)(dF/dx)$ and of heat liberation $\Delta q = (1/cT_s)(dq/dx)$;

(e) the possible occurrence of critical flow regimes in those cases where the zone of spontaneous condensation is located in the region of transonic flow velocities.

As numerous calculations showed [13], for the conditions of steam flow in moist-steam stages of turbines and other power plants, the indicated quantities change in the following ranges: $\Delta T = 28-42$ K, $\Delta\overline{T} = \Delta T/T_s = 0.08-0.13$, $\Delta y_l = 0.0001-0.0003$, $\Delta y = 0.025-0.035$, $\Delta q = 40-80$ J/kg, $\Delta\tau = 0.05-0.1$ msec, $\Delta\overline{q} = 0.5-1.5$ 1/m, $\Delta F = 0.001-1.0$ 1/m.

There is one other special feature of such flows, which is an anomalous change in the temperature T and supercooling ΔT in the zone of spontaneous condensation at transonic flow velocities.

We shall restrict ourselves for simplicity to consideration of a one-dimensional flow for which the system of equations under the conditions generally accepted for such problems [4] can be written in the form

$$dM/M = \frac{1 + \kappa_1/2M^2}{M^2 - 1}\left[\frac{dF}{F} - \frac{1 + \kappa M^2}{2 + \kappa_1 M^2}\left[\frac{B_1 dy}{1 - y} - \frac{y di'}{(1 - y)\, c'' T}\right]\right],$$

$$dp/p = \frac{\kappa M^2}{M^2 - 1}\left[\frac{dF}{F} - B_1\frac{dy}{1 - y} - \frac{y di'}{(1 - y)\, c'' T}\right],$$

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$$dp/\rho = \frac{M^2}{1 - M^2}\left[\frac{dF}{F} - \frac{1}{M^2}\left[\frac{(M^2 - B)\,dy}{1 - y} + \frac{ydi'}{(1 - y)\,c''T}\right]\right],$$

$$dT/T = \frac{(\kappa - 1)\,M^2}{1 - M^2}\left[\frac{dF}{F} + \left[1 - B\frac{\kappa M^2 - 1}{(\kappa - 1)\,M^2}\right]\frac{dy}{1 - y} + \frac{\kappa M^2 - 1}{(\kappa - 1)\,M^2}\frac{ydi'}{(1 - y)\,c''T}\right]. \qquad (*)$$

Here $\kappa_1 = \kappa - 1$, $B_1 = B - 1$, $B = 1/c''T[r + c''(T - T_s) + c'(T_s - T')]$.

Availing ourselves of the well-known Clapeyron–Clausius relation for the phase-equilibrium curve $dp/dT_s = r/T_s(v_s'' - v_s') = r/\varepsilon T_s v_s''$ and of the vapor-phase equation of state $pv'' = \alpha RT$, we rewrite the first equation in the form $dT_s/T = \omega_1 dp/p$, where $\varepsilon = 1 - v'/v''$ and $\omega_1 = \alpha\varepsilon RT_s^2/r$. This allows one to write an equation just for the supercooling $\Delta T = T - T_s$ as

$$\frac{d\Delta T}{T} = \frac{(\omega\kappa - 1)\,M^2}{M^2 - 1}\left[\frac{dF}{F} + \left[\frac{(\omega\kappa M^2 - 1)\,B}{(\kappa\omega - 1)\,M^2} - 1\right]\frac{dy}{1 - y} + \frac{\omega\kappa M^2 - 1}{\omega\kappa M^2}\frac{ydi'}{(1 - y)\,c''T}\right],$$

where $\omega = 1 - \omega_1 = 1 - \alpha\varepsilon RT_s^2/r$. We note that the magnitude of the third term in this and all the rest of the similar previous equations does not exceed 2–3% of the first two, and it can be easily neglected.

In the range of pressure change from 0.003 to 3.0 MPa, the values of ω and B for steam change from 0.95 to 0.90 and from 4.3 to 1.5, respectively.

As is seen from the equation obtained, the geometric effect (dF) in a convergen-divergent channel is responsible for the deeper supercooling in both sub- and supersonic regions of the flow. On the other hand, the result of the condensation effect (dy) is determined by the sign of the preceding coefficient. We can easily see that at all the values of $M > 1$ this coefficient is positive and, consequently, condensation lessens the supercooling.

When $M < 1$, the sign of the coefficient changes in transition through $M^* = \{B/[1 + \omega\kappa(B - 1)]\}^{1/2}$: it is negative for $M < M^*$, and condensation diminishes the supercooling, but it is positive for $M > M^*$, and condensation aggravates the supercooling.

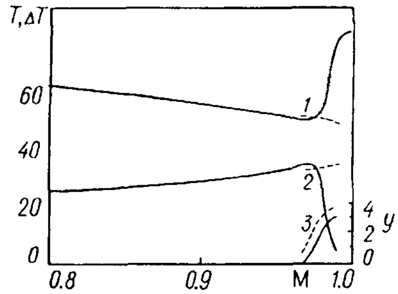
As is seen from the equation (*), the temperature of steam also changes in a similar manner, i.e., condensation leads to an increase in temperature in the entire range of M numbers except for the zone $1 > M > M^{**}$, in which temperature decreases. Here $M^{**} = \{B/[1 + \kappa(B - 1)]\}^{1/2}$. The expanation of this effect is that the condensation heat supplied in this zone is insufficient for flow acceleration and the resulting deficit is made up at the expense of the internal energy of the gas. An appropriate analog to such an anomalous change in temperature would be the effect, known from the theory of heat nozzles [5], consisting in a decrease in the temperature of a gas, which is accelerated on addition of heat at subsonic velocities in the range $1 > M > M^{**}$, where $M^{***} = \{1/\kappa\}^{1/2}$.

The initial system of equations also incorporates heat and mass exchange in a two-phase condensing flow. It can be easily shown that if we neglect the change in the vapor-phase flow rate, to which the condition $B >> 1$ formally corresponds, then the expressions for M^* and M^{**} will take the form $M^* = \{1/\omega\kappa\}^{1/2}$ and $M^{**} = \{1/\kappa\}^{1/2}$. This agrees completely with the results for a heat nozzle. As is seen, the flow-rate effect somewhat decreases the region of anomalous change in the temperature and supercooling of steam.

Calculations show that in the range of pressure change from 0.003 to 3.0 MPa the characteristic values of M numbers are $M^* = 0.92$–0.98, $M^{**} = 0.90$–0.96, and $M^{***} = 0.88$–0.89.

The actual change in the temperature and supercooling of steam in a channel is determined by the overall geometric and condensational effect on the flow. If the indicated anomaly occurs, which is most probable for low-gradient channels, then it aggravates the crisis character of condensed vapor flow, since increase in supercooling intensifies the processes of nucleation and growth of drops.

As an example, Fig. 1 shows the change in the characteristic parameters of vapor in the region of initial condensation for two channels with different gradients of expansion calculated using the "Moist vapor" package of applied programs [6]. An anomalous increase in the supercooling of vapor in the zone of spontaneous condensation occurs only in a low-gradient channel.



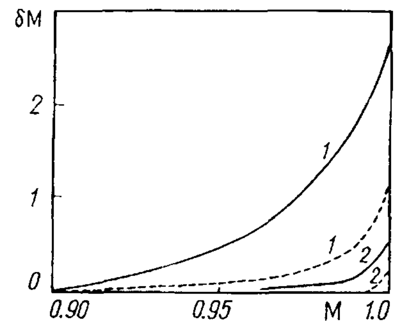


Fig. 1. Distribution of the flow parameters along the nozzle (solid curves, $dF/dx = -10^3$ 1/m; dashed curves, $dF/dx = -1$): 1) T, 2) ΔT, 3) y. °C; y, %.

Fig. 2. Error of numerical calculation (solid curves, initial equation; dashed curves, improved equation) for the integration steps (dimensionless): 1) 0.01; 2) 0.005. δM, %.

In conclusion, we will consider one computational aspect. It is known that the error of calculations by initial equations in the transonic region increases sharply, since they have singularity at the point M = 1. A substantial increase in the accuracy of calculations by simple methods is achieved [7] in this region by transition to the new variables μ, π, and ξ defined by the formulas

$$\mu = [\mathrm{M}^2 - 1]^2/4, \quad \pi = p \exp[-\kappa\sqrt{\mu}/a_1], \quad \zeta = w \exp[-\sqrt{\mu}/a_1\mathrm{M}^2],$$

where $a_1 = 1 + (\kappa - 1)\mathrm{M}^2/2$.

The result will be illustrated with the simplest example of a single-phase adiabatic flow, for which the initial equation for the Mach number $d\mathrm{M}/dx = a_1\mathrm{M}^2/(\mathrm{M}^2 - 1)dF/dx$ in transition to the variable μ is transformed to $d\mu/dx = a_1(1 - 2\mu^{1/2})dF/dx$. The results presented in Fig. 2 testify to the reduction in the error of calculation by at least 3–5 times.

NOTATION

F, flow area of the channel; M, Mach number; w, p, T, ρ, v, i, c, velocity, pressure, temperature, density, specific volume, enthalpy, and heat capacity (′, liquid phase; ″, vapor phase); y, mass degree of moisture content; r, heat of vaporization; R, gas constant; κ, specific-heat ratio; α, coefficient of vapor-phase compressibility. Subscript: s, saturation.

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