

HEAT AND MASS TRANSFER ZONE IN AN AIR-WATER JET THROUGH A SODIUM NITRATE MELT

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Derived are empirical formulas for calculating the dimensions of the heat and mass transfer zone in a sodium nitrate melt at a 623°K temperature.

The interaction between a gas jet and a liquid ("needle" jet) [1, 2] is effective when used for thoroughly dehydrating not highly active liquid residues in special water purification vats in atomic-electric power plants or wastes from radiochemical laboratories, where sodium nitrate constitutes 80-90% of the total salt content. Dehydration is effected by injecting an air jet with a mist of solutions or suspensions into the superheated melt of the residue.

This method can also be used for cooling high-temperature liquid media through a direct contact with water, by injecting into them an air-water mixture [3] or for prevaporizing salt solutions into high concentrates, in order to obtain a fluidized granular product [4].

When an air jet is injected into a liquid (salt solution or another high-temperature heat carrier), the latter is brought into the jet and broken down into droplets [1].

When a two-phase jet (air-solution, air-suspension, or air-water) is discharging into the liquid, it still contains droplets of the sprayed phase. Between hot droplets of the impelled phase on the one side and cold droplets of the sprayed phase on the other side there will occur certain heat and mass transfer processes (heatup, evaporation, melting, and superheating the melt). For this reason, the jet becomes highly anisothermal and constitutes a zone of intensive heat and mass transfer [5-7].

To calculate the kinetics of heat and mass transfer processes in a jet is a difficult problem. The dimensions of the heat and mass transfer zone, which determine the necessary size of the technical equipment, can be defined on the basis of its temperature field boundaries. Thus, the temperature at the boundaries of this zone is equal to the temperature of the melt mass in the case of a dehydration setup or equal to its temperature at the exit section of the heat exchanger in the case of cooling a high-temperature heat carrier.

Published data from which one could calculate the dimensions of the heat and mass transfer zone in dehydrators of liquid radioactive wastes with a high content of sodium nitrate or other salts pertain mainly to fluidization systems [8, 9]. In order to obtain data for calculating the dehydration in a melt, therefore, experiments were performed for determining the dimensions of the heat and mass transfer zone during injection of an air-water jet into molten sodium nitrate at a 623°K temperature — experiments which fairly accurately simulated the actual process.

The test apparatus shown in Fig. 1 consisted of a vertical column 210 mm in diameter and 1400 mm high. The lower part, 350 mm high, was the melting pot. Five electric heaters in tubular sheaths 60 mm in diameter were spaced around a circle 145 mm in diameter inside the melting pot.

In the stuffing box at the bottom of the melting pot was mounted a pneumatic internal-displacement sprayer in a vertical upward position, with the nozzle flush against the bottom of the melting pot at the center. The upper part of the column was the separator chamber for extracting droplets of melt from the

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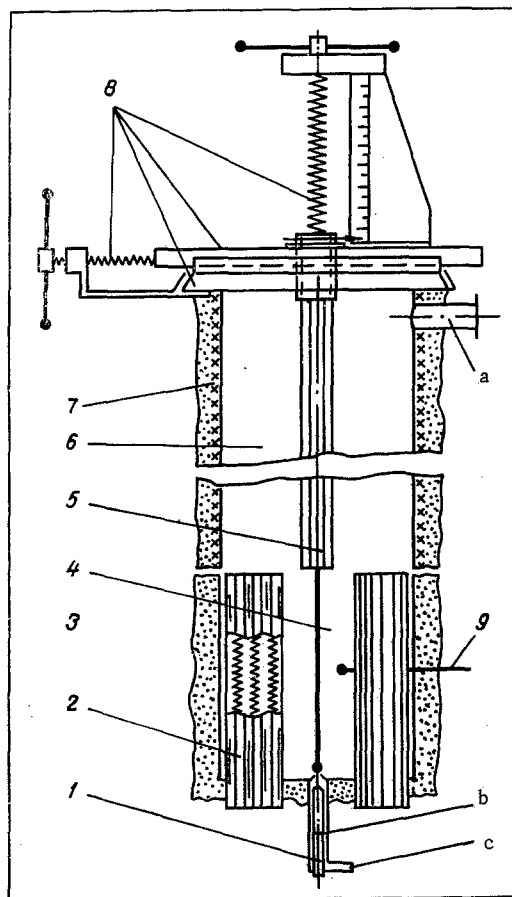


Fig. 1. Test apparatus: 1) sprayer, 2) heater sheath, 3) heater, 4) melting pot, 5) well of the movable thermocouple, 6) separator chamber, 7) heater, 8) device for moving the thermocouple and fixing it in position, 9) thermocouple, a) outlet for vapor-air mixture, b) water inlet, c) air inlet.

vapor-air stream. In order to prevent crystallization of the salt or formation of a slag, the walls of the separator chamber were heated electrically.

The temperature of the molten salt was measured with two Chromel—Alumel thermocouples installed in the pot, the readings recorded through automatic potentiometer instruments. The fixed thermocouple was placed inside a tubular well and soldered to the wall of the melting pot 180 mm above the bottom. The end of the thermocouple well cleared the wall by 15 mm. The movable thermocouple was also installed inside a well. Its hot junction could be moved to and fixed at any position inside the melting pot relative to the spray nozzle.

The tests were performed in the following sequence. As air was supplied to the sprayer, a certain amount of sodium nitrate was entered into the apparatus and the electric heaters were turned on. After the salt had been melted and heated up to 623°K, a measured quantity of water was added to the sprayer. The temperature of the molten salt (indicated by the fixed thermocouple) was held at the required level by regulating the electric heater power through model RNO-250-10 voltage regulators. The flow rates of water and air were measured with model RS glass rotameters, and the pressure of air before entering the sprayer was measured with a standard manometer on the 0-24,500 N/m² scale. After a constant temperature had been established in the melt, the temperature in the pot was measured with the movable thermocouple along the jet axis coinciding with the sprayer axis and also across transverse jet sections. A total of 200 tests was performed using sprayers with discharge orifices 1.5, 2.1, 2.55, 3.0, and 3.55 mm in diameter, at a flow rate of the air-water mixture ranging within 6-20 kg/h and the water concentration ranging from 0.56 to 0.91 kg/kg.

The tests indicated a temperature variation along the jet axis away from the spray nozzle (Fig. 2a) from that of the entering mixture to that of the sodium nitrate melt, and across transverse sections at various horizontal levels (Fig. 2b) from that at the jet axis to that of the sodium nitrate melt. A uniform temperature in the remaining mass of melt was attained by thorough mixing. According to Fig. 2, the temperature variation along the jet axis was smooth, while across a transverse section it was irregular (first sudden, then smooth).

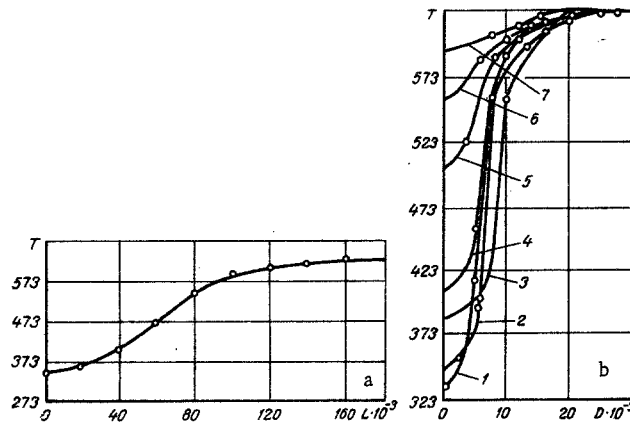


Fig. 2. Trend of the temperature variation: (a) along the sprayer axis ($G_{\text{mix}} = 13.4$ kg/h, $G_W/G_{\text{mix}} = 0.63$, $d = 3$ mm), (b) across the reaction zone ($G_{\text{mix}} = 12.7$ kg/h, $G_W/G_{\text{mix}} = 0.66$, $d = 3$ mm), distance from the nozzle axis 5 mm (1), 10 mm (2), 25 mm (3), 45 mm (4), 60 mm (5), 75 mm (6), 90 mm (7). Temperature T ($^{\circ}\text{K}$), distance from the nozzle L (m), distance from the sprayer axis D (m).

On the basis of the temperature trend in the jet, one could conclude that the disperse phase heated up and evaporated, whereupon the new phase became superheated.

As the length of the heat and mass transfer zone we defined the distance along the sprayer axis from the nozzle to the point with a temperature 10% below the temperature of the bulk of the melt. The temperature profile across a transverse section of the jet was symmetrical with respect to the jet axis. As the width of the heat and mass transfer zone, therefore, we defined double the distance from the jet axis to the point with a temperature 10% below the temperature of the bulk of the melt.

According to Fig. 2b, the width of the zone first increases with the distance from the nozzle and then decreases again, i. e., the heat and mass transfer zone is one with closed boundaries.

The dimensions of the heat and mass transfer zone in devices with "needle" jets depend on the process rates in it. These, in turn, depend on the degree ε to which the jet gas and the liquid from which it discharges have intermixed [1, 10].

Parameter ε , which characterizes the mutual penetration of both phases, the increase in the interphase boundary surface, and the gas-liquid interaction energy, is usually defined in terms of a jet composition or a jet nonuniformity ratio [1]. For instance, the intermixture ratio of a cold jet gas and a liquid can be defined as the ratio of the temperature difference between any point on the jet axis and the ambient liquid to the temperature difference between the nozzle throat and the ambient liquid, if it is assumed — to the first approximation — that the velocity profile and the temperature profile in the jet are similar. The correctness of this assumption has been verified experimentally [11] for jet with a uniform density.

The intermixture of jet air with molten sodium nitrate can then, on the basis of this assumption and the results in [10], be described by the following expression

$$\varepsilon = \frac{t_x - t_{\text{melt}}}{t_a - t_{\text{melt}}} = f(X/d; \text{Ar}) \quad (1)$$

Applied to the particular case on hand, the intermixture ratio ε_1 of the air-water jet with the sodium nitrate melt must depend strongly on the water concentration in the mixture discharging from the nozzle, inasmuch as the main portion of the dissipated heat determining the temperature change in the heat and mass transfer zone is used up on vaporizing the moisture and superheating the vapor. Therefore, relation (1) becomes

$$\varepsilon_1 = \frac{t_x - t_{\text{melt}}}{t_a - t_{\text{melt}}} = f_1(X/d; \text{Ar}; G_W/G_{\text{mix}}) \quad (2)$$

The Archimedes number in this expression includes the velocity w_j and the density ρ_j of the air-vapor jet at the nozzle exit.

The absolute value of parameter ε_1 , according to this definition, varies from 0 to 1. At the boundary of the temperature-defined heat and mass transfer zone the value of ε_1 is near zero. For the boundary of this zone, then, Eq. (1) becomes

$$f_1(X/d; Ar; G_W/G_{mix}) = 0. \quad (3)$$

With condition (3) satisfied, the dimensionless distance X/d from the nozzle, measured in nozzle diameters, represents the length of the heat and mass transfer zone, i. e.,

$$X/d = f_2(Ar; G_W/G_{mix}). \quad (4)$$

In the mathematical evaluation of the test data we searched for a power-law form of function (4). With the aid of a "Nairi" computer, the method of least squares has, indeed, yielded equations for the length (L_z) and the maximum width (D_z) of the heat and mass transfer zone during evaporation of an air-water jet in a sodium nitrate melt at a 623°K temperature:

$$L_z/d = 11.5 Ar^{0.34} (G_W/G_{mix})^{1.7}, \quad (5)$$

$$D_z/d = 5.15 Ar^{0.2} (G_W/G_{mix})^{1.1}. \quad (6)$$

These equations indicate that the dimensions of the heat and mass transfer zone depend strongly on the water concentration in the discharging jet and depend less on the Archimedes number. The power exponent is higher in the expression for the zone length than in the expression for the zone width. This is probably because of the smaller radial than axial velocity component at any jet section [11] and because of the larger distances which the droplets in the jet have time to traverse before their temperature becomes equal to the temperature of the surrounding melt.

Equations (5) and (6) approximate our test data within $\pm 18\%$. The correlation factor, which characterizes the degree of linearity between the logarithms of the zone dimensions and the logarithms of the Archimedes number and of the G_W/G_{mix} simplex, is equal here to 0.8 and 0.75 respectively. Equations (5) and (6) are valid within the ranges $Ar = 20-100$ and $G_W/G_{mix} = 0.56-0.91$.

The derived equations may be useful in the design of heat and mass transfer apparatus with a "needle" jet for complete dehydration of radioactive vat residues with a high content of sodium nitrate or other salt solutions, considering that these equations are based on experiments which adequately well simulated such processes.

NOTATION

$\varepsilon, \varepsilon_1$	are the intermixture ratio of sodium nitrate melt with an air or an air-water jet respectively;
t_x, t_a, t_{melt}	are the temperature at any point along the jet axis, at the sprayer nozzle exit, and of the surrounding melt respectively;
X	is the distance of a point from the nozzle, along the jet axis;
d	is the diameter of the discharge orifice of the nozzle;
$Ar = \rho_A/\rho_{melt} w^2/gd$	is the Archimedes number for an air jet discharging into a melt;
w	is the velocity of adiabatic flow of an air jet;
$\rho_A, \rho_{melt}, \rho_W$	are the density of air jet at the nozzle throat after adiabatic discharge, of molten sodium nitrate, and of water respectively;
$G_{mix} = G_W + G_A$	is the weight flow rate of air-water mixture;
G_W	is the weight flow rate of water;
G_A	is the weight flow rate of air;
$w_j = w(1 - G_W/G_{mix})$	is the velocity of air-water jet discharge;
$\rho_{mix} = (G_{mix})/(G_W/\rho_W + G_A/\rho_A)$	is the density of air-water mixture;
L_z	is the length of heat and mass transfer zone;
D_z	is the maximum width of heat and mass transfer zone.

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