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QUENCHING OF AN AIR PLASMA BY SOLID PARTICLES

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An analytical expression which describes the quenching of a relatively cold plasma by cold solid particles is used for designing the length of the quenching reactor. The cooling law thus obtained agrees with experimental data.

Quenching of the products of plasmochemical reactions is one of the governing stages, especially of processes yielding bound nitrogen or acetylene [1-3]. Among the most effective methods of quenching is injection of the plasma into a fluidized bed or, conversely, injection into the plasma jet of cold solid particles acting as the intermediate heat carrier [4-6]. Results of calculations of the heat transfer from plasma to solid particles have been presented in other reports [7-9] in either numerical or criterial form. No simple expressions are given there, however, which would be convenient to use for practical calculations. In order to obtain such expressions, we will here find an analytical solution to the problem of heat transfer from a gas (originally plasma) stream to solid particles.

We consider a cylindrical channel of length l and diameter d. The channel axis coincides with the X axis of coordinates. At the X = 0 section of the channel a gas stream enters carrying spherical solid particles of the same diameter D. The gas velocity is $W_0 \gg W_s$ (soaring velocity). We assume that all motion is steady and the gas flow is one-dimensional. The latter assumption implies that the gas velocity and temperature at any X do not vary along Y and Z. When the solid particles in the gas stream are uniformly distributed over the cross section of the latter, then to each solid particle corresponds a definite mass of gas (gaseous "particle").

The equations of heat transfer according to Newton's law and the equation of heat balance are

$$-mc_p dT = m_s c_{ps} dT_s = \alpha F (T - T_s)\, dt, \quad (1)$$

$$-\frac{d}{dt}(T - T_s) = \alpha F \left(\frac{1}{mc_p} - \frac{1}{m_s c_{ps}}\right)(T - T_s), \quad (2)$$

$$\int_{T_0}^{T_f} mc_p dT = \int_{T_{sf}}^{T_{s0}} m_s c_{ps} dT_s . \quad (3)$$

The energy balance (3) yields

$$\frac{m_s}{m} = \frac{G_s}{G} = \frac{\int_{T_0}^{T_f} c_p dT}{\int_{T_{sf}}^{T_{s0}} c_{ps} dT} \quad (4)$$

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TABLE 1. Temperature Dependence of the Criterial Numbers and of the Quantity $\lambda N_{Nu}/c_pT$ at Various Values of W, D, and N_{Re}

T, °K	3300	2800	2300	1800	
$Pr^{1/3}$	0,82	0,82	0,845	0,88	
Re	0,335	0,39	0,46	0,55	$\rho = 10^{-1}$ kg/m^3; WD = $3.5 \cdot 10^{-4}$ m^2/sec
Nu	2,285	2,307	2,344	2,39	$\rho = 10^{-1}$ kg/m^3; WD = $3.5 \cdot 10^{-4}$ m^2/sec
$\frac{\lambda Nu}{c_pT} \cdot 10^{-4}$	1,34	1,33	1,21	1,24	WD = $3.5 \cdot 10^{-4}$ m^2/sec; Re = 0.335–0.55
$\frac{\lambda Nu}{c_pT} \cdot 10^{-4}$	1,7	1,7	1,6	1,6	WD = $3.5 \cdot 10^{-3}$ m^2/sec; Re = 3.35–5.5
$\frac{\lambda Nu}{c_pT} \cdot 10^{-4}$	2,83	2,89	2,81	3,04	WD = $3.5 \cdot 10^{-2}$ m^2/sec; Re = 33.5–55

and, inasmuch as

$$\frac{G_s}{G} = K, \quad \int_{T_0}^{T_f} c_p dT = -\bar{c}_p (T_0 - T_f),$$

$$K = \frac{\bar{c}_p (T_0 - T_f)}{\bar{c}_{ps} (T_{sf} - T_{s0})}, \tag{5}$$

Eq. (2) can be rather easily solved in three approximations:

1) $K \gg 1$, quenching of the gas stream with almost no heating of the particles;

2) $K \ll 1$, overheating of the particles to evaporation;

3) $K \approx 1$, heat transfer with retention of a high thermal potential at the particles.

In this study we consider the first case. When $K \gg 1$, then the $1/m_s c_{ps}$ term in Eq. (2) can be disregarded and

$$-\frac{d}{dt}(T - T_s) = \frac{\alpha F}{mc_p}(T - T_s). \tag{6}$$

From the expression for the Nusselt number we have $\alpha = \lambda N_{Nu}/D$, where N_{Nu} is referred to one solid particle of diameter D. Let us use the relation [10]

$$Nu = 2 + 0.6\, Re^{1/2} Pr^{1/3}, \tag{7}$$

although more exact ones are known [9,11].

It is shown in Table 1 that the quantity $\lambda N_{Nu}/c_pT$ is almost (within ±10% accuracy) independent of the temperature over the 3500–1800°K range for three ranges of the Reynolds number:

$$0.335 < Re < 0.55, \; 3.35 < Re < 5.5, \; 33.5 < Re < 55.$$

On the basis of the data in Table 1, we can rewrite the coefficient on the right-hand side of Eq. (6) as

$$\frac{\lambda\, Nu\, F}{mc_p} = \frac{\lambda_0\, Nu\, F}{mc_{p0}} \left(\frac{T}{T_0}\right). \tag{8}$$

The temperature range for air has been selected considering that the decomposition of nitrogen oxide becomes a "frozen in" reaction below 1800°K and that heating the gas above 3500°K serves no purpose, because the much too high speed of the decomposition reaction makes quenching of nitrogen oxide entirely impossible [2,3].

The last assumption needed for solving Eq. (6) is a constant pressure along the channel axis.

From the equation of continuity and the equation of state we obtain

$$\rho W = G/S; \; P/\rho = gRT; \; W = \frac{GgR}{SP} T = kT. \tag{9}$$

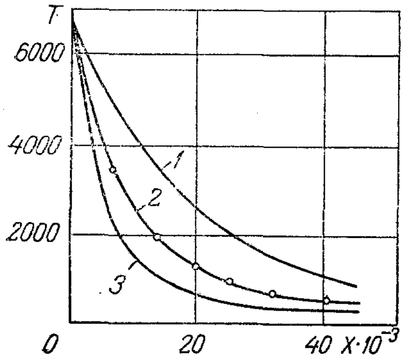

Fig. 1. Temperature T (°K) as a function of the X coordinate (10^{-3} m), for K = 30, 50, 100 (curves 1, 2, 3 respectively); dots represent data from [4].

It follows that $W/W_0 = T/T_0$. An expression analogous to expression (9) was used in another study [4] for evaluation of experimental data.

Inserting into Eq. (6) expressions (8) and (9) successively, with the substitutions

$$F = nD^2;\ 1/m = K/m_s = 6K/nD^3\rho_s,$$

we obtain

$$A = \frac{6\lambda_0 \mathrm{Nu}}{c_{p0}\rho_s D^2} K.$$

Taking into account that $W dt = dX$, we then integrate Eq. (6) for the initial conditions $t = 0$, $X = 0$, $T = T_0$, and $T_s = T_{s0}$ so that

$$T - T_s = (T_0 - T_{s0}) \exp\left(-\frac{A}{W_0} X\right). \tag{10}$$

When $K \gg 1$, then $T_s \approx T_{s0}$ and we obtain exactly the same expression as the one obtained empirically [4]

$$T - T_{s0} = (T_0 - T_{s0}) \exp(-cX), \tag{11}$$

where $c = A/W_0$ is a constant [4].

In this way, the constant in the power exponent in the empirical cooling law has acquired from the analytical solution a definite physical significance.

Differentiating expression (11) with respect to time and expanding the exponential term into a series yields, if only the first two terms of the series are retained, the quenching rate

$$-\frac{dT}{dt} = (T_0 - T_{s0}) A \left(\frac{W}{W_0}\right)\left(1 - \frac{A}{W_0} X\right). \tag{12}$$

At $t = 0$ and $X = 0$, with $W = W_0$, the initial quenching rate becomes

$$-\left(\frac{dT}{dt}\right)_0 = A(T_0 - T_{s0}). \tag{13}$$

For designing a reactor and for an experiment it is more convenient to use the derivative of temperature T with respect to coordinate X, namely

$$-\frac{dT}{dX} = (T_0 - T_{s0}) \frac{A}{W_0}\left(1 - \frac{A}{W_0} X\right). \tag{14}$$

The reactor length can be calculated from Eq. (10)

$$l = \frac{W_0}{A} \ln\left(\frac{T_0 - T_{s0}}{T_f - T_{sf}}\right). \tag{15}$$

For a given quenching rate $(dT/dt)_0$ and initial temperatures of the gas and of the solid particles one can establish the constraint on the size of particles of a certain material

TABLE 2. Dependence of the Reactor Length and of the Quenching Rate on the Size of Coolant Particles, at Initial Stream Velocities of 50, 100, and 300 m/sec

D, m	W_0, m/sec: 50		100		300	
	l, m	$\left(\frac{dT}{dt}\right)_0$, $\frac{°C}{sec}$	l, m	$\left(\frac{dT}{dt}\right)_0$, $\frac{°C}{sec}$	l, m	$\left(\frac{dT}{dt}\right)_0$, $\frac{°C}{sec}$
10^{-5}	$1{,}5\cdot10^{-3}$	$3{,}5\cdot10^{8}$	$1{,}06\cdot10^{-2}$	$3{,}6\cdot10^{8}$	$2{,}1\cdot10^{-2}$	$4{,}1\cdot10^{8}$
10^{-4}	0,5	$4{,}4\cdot10^{6}$	0,88	$5{,}4\cdot10^{6}$	2	$6{,}9\cdot10^{6}$
10^{-3}	4,4	$5{,}1\cdot10^{4}$	45	10^{5}	83	$1{,}56\cdot10^{5}$

$$D^2 = \frac{6\lambda_0 \mathrm{Nu}}{A\rho_s c_{p0}} K, \tag{16}$$

with K known, of course. It is generally difficult, however, to determine the quantity $K = m_s/m$ experimentally. It is more expedient to stipulate it in the form (5) and then write

$$A = \frac{6\lambda_0 \mathrm{Nu}}{D^2 c_{p0}\rho_s} \; \frac{\bar{c}_p (T_0 - T_f)}{\bar{c}_{ps}(T_{sf} - T_{s0})}. \tag{17}$$

Expression (17) contains measurable quantities and handbook data, which makes it possible to complete the calculations.

The validity of the assumptions could be verified by comparing the numerical value of coefficient c in [4] with its value according to expression (17). However, the data in [4] do not render expressions (5) or (17) suitable for determining K.

Results of calculations based on Eq. (10) for various values of K are shown in Fig. 1. The dots on this graph represent data from [4].

For plotting the graph, the N_{Nu} value for argon was taken from [11] and the values of λ_0 and c_{p0} were taken from [12]. The values of T_0, T_{s0}, D, and ρ_s are the same as in [4].

The graph indicates a close fit of experimental points on the curve calculated for K = 50. This is equal to $0.22K_0$ for the fluidized bed into which plasma was injected in the experiment [4]. Such a decrease of the mean density of particles in a plasma jet has been well explained [13] on the basis of a "two zone" model with one zone of pure gas and another zone of a gas–particles mixture. The hydrodynamics of a fluidized bed need not be analyzed here, inasmuch as this has already been done [8,9,14] and the case of plasma injection into a fluidized bed has been dealt with thoroughly in another study [13]. It must be noted, however, that generally N_{Nu} in Eq. (10) depends on the velocity W_s of a solid particle, implicitly through N_{Re}. In turn $W_s = f(X)$, by virtue of nonisothermality of the stream, even within such imposed constraints as one-dimensional flow and uniform distribution of solid particles. An analysis of such a dependence will apparently lead to the cooling law [15]

$$-\frac{dT}{dt} = \beta T^2. \tag{18}$$

On the basis of this analytical solution, a reactor was designed for quenching nitrogen oxide. The reactor length l and the initial quenching rate $(dT/dt)_0$, both depending on the initial stream velocity and on the size of the solid particles, are given in Table 2. The calculations were based on air as the gas and nickel as the material of solid particles, $T_0 = 3300°K$, $T_f = 1000°K$, $T_s = 600°K$, and almost constant, K = 50.

The obtained solution (11), transformed to

$$\frac{1}{T} = \frac{1}{T_{s0}} + \left(\frac{1}{T_0} - \frac{1}{T_{s0}}\right)\exp(-bt), \tag{19}$$

is finally put in the general form [2, 3]

$$\frac{1}{T} = \frac{1}{T_0} + at. \tag{20}$$

This form of the expression in turn yields a relation to kinetic quenching of nitrogen oxide by another mechanism [15] and the degree of its retention [2,3].

NOTATION

t, time; T, stream temperature; λ, thermal conductivity of the gas; c_p, specific heat of the gas; ρ, density; P, static pressure; R, gas constant; G, mass flow rate of the gas; D, diameter of a spherical solid particle; F, surface area of a solid particle; d, channel diameter; l, channel length; S, channel cross section; α, heat transfer coefficient; X, space coordinate; g, acceleration due to gravity; W_s, soaring velocity; and $\bar{c}_p$, mean (over the temperature range) specific heat. Subscripts: 0, parameters at the channel inlet; f, parameters at the channel outlet; s, parameters of a solid particle; and A, k, a, b, β, c, intermediate constants.

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