EXPERIMENTAL INVESTIGATION OF THE RATE OF PHASE AND CHEMICAL TRANSFORMATIONS IN A HIGH-VELOCITY HIGH-TEMPERATURE STREAM

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A procedure for the experimental–theoretical investigation of the evaporation and combustion of a liquid injected into a supersonic high-temperature stream is proposed.

The kinetics of phase and chemical transformations at high temperatures and high flow velocities are of great concern in a wide range of practical problems. In viev of the complexity of a direct analysis of these phenomena (according to the temperature of the mixture, chemical composition, etc.), it appears more promising to determine the rates of these processes from their final effect, the change in the static pressure of the stream along the channel.

This effect is very pronounced and may be easily and accurately measured, especially at supersonic velocities of the flux of reacting mixture. Thus, for example, the evaporation of 10% kerosene in a homogeneous hot mixture moving with supersonic velocity at M = 2.5 produces a pressure drop of approximately 15% below the level in the absence of evaporation. For the flow of such a mixture with complete combustion of the fuel, the pressure in a cylindrical channel should increase by approximately 100%.

Obviously, the change in static pressure in a channel is the result of many factors acting simultaneously on the flow: friction along the channel wall, heat transfer to the wall, mechanical action of the injected liquid and its infusion, evaporation, decomposition, combustion. The problem is that in order to investigate the rate of any particular component process (e.g., combustion), it is necessary first to determine the rates of all the others. In this case the rate of the process under consideration can be determined from the condition that its effect on the pressure change, in combination with the already known (or determined) effects, must yield the measured value of this change. The problem thus reduces to matching the rate of that given process within a given channel segment so as to reconcile the calculated and the tested change in pressure (considering all effects). Let us see how this can be accomplished in practice.

The change in static pressure in a one-dimensional stream along an elementary segment dl of the channel is expressed by the relation [1]:

$$\frac{dP}{P}=\frac{kM^2}{1-M^2}\cdot\frac{dF}{F}-\frac{kM^2\left(1+\frac{k-1}{2}M^2\right)}{1-M^2}\cdot\frac{dT^*}{T^*}-\frac{kM^2[1+(k-1)M^2]}{2(1-M^2)}\left(\xi\frac{dl}{D}+2\frac{d\bar{x}}{kPFM^2}-2y\frac{dm}{m}\right)$$

$$-\frac{2kM^2\left(1+\frac{k-1}{2}M^2\right)}{1-M^2}\cdot\frac{dm}{m}+\frac{kM^2}{1-M^2}\cdot\frac{d\mu}{\mu}. \tag{1}$$

The increments of variables in Eq. (1) during phase and chemical transformations, dT^*/T^*, $\xi dl/D$, $d\bar{x}/kPFM^2$, dF/F, and $d\mu/\mu$, are considered in turn.

dT^*/T^* is the change in stagnation temperature of the stream. The total enthalpy of the gas + liquid mixture, without accounting for the latent heats of phase and chemical transformation, can be written as

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$$I = m_g c_p T^* + m_j c_{p_j} T_j + m_j \frac{W_j^2}{2}.$$

A change in this quantity dI over the length of a channel segment is determined by the heat transfer to the channel wall dQ_{cool}, the heat of evaporation of some liquid dQ_{evap}, and the heat of the chemical reaction dQ_{chem}:

$$dI = -dQ_{\mathrm{cool}} - dQ_{\mathrm{evap}} + dQ_{\mathrm{chem}}$$

or

$$m_g c_p dT^* + m_g T^* dc_p + c_p T^* dm_g + d(m_j c_{p_j} T_j) + d\left(m_j \frac{W_j^2}{2}\right) = dQ_{\mathrm{chem}} - dQ_{\mathrm{evap}} - dQ_{\mathrm{cool}},$$

from which

$$\frac{dT^*}{T^*} = \frac{dQ_{\mathrm{chem}} - dQ_{\mathrm{evap}} - dQ_{\mathrm{cool}} - T^* d(mc_p) - d\left(m_j c_{p_j} T_j + m_j \frac{W_j^2}{2}\right)}{m_g c_p T^*}. \qquad (2)$$

In this specific case the heat dissipation into the surrounding space can be reduced to an amount which is negligibly small in comparison with the thermal effect of phase and chemical transformations [2] so that the process occurring inside the tube may be considered thermally insulated: $dQ_{\mathrm{cool}} = 0$,

$$dQ_{\mathrm{evap}} = L_{\mathrm{evap}} dm, \quad dQ_{\mathrm{chem}} = Q_{\mathrm{chem}}(\alpha, T)\, dm_{\mathrm{chem}}, \qquad (3)$$

where $Q_{\mathrm{chem}}(\alpha, T)$ is the thermal effect of the chemical reaction per unit weight of the reacting substance at given values of excess oxidizer α and mixture temperature T.

$\xi dl/D$ is the friction through distance dl. This parameter can be determined by a blow test in an empty experimental channel, or can be calculated by known formulas.

$d\bar{x}/kPFM^2$ is the drag of the injected liquid particles (droplets) suspended in the stream within a given segment of the channel

$$d\bar{x} = \sum_1^n \sum_1^m d\bar{x}_{ij}, \qquad (4)$$

where n is the number of categories in the size spectrum of droplets (depending on the desired precision) and m is the number of droplets in one i-th category.

The drag of a single evaporating droplet can be determined according to the formula:

$$d\bar{x}_d = C_d(\mathrm{Re})\, \psi(\mathrm{We})\, F_d \rho_g \frac{W_d dW_d}{2}, \qquad (5)$$

where $C_d(\mathrm{Re})$ is the drag coefficient for a spherical droplet and $\psi(\mathrm{We})$ is a correction factor to account for the deformation of the droplet in the stream.

The initial dispersion spectrum of the injected liquid as well as $C_d(\mathrm{Re})$ and $\psi(\mathrm{We})$ can be calculated by the conventional method in [3].

In order to calculate the drag of droplets in the stream, it is necessary to know the change in their dimensions through every segment along the entire channel. For this purpose, the change in the droplet diameter of every category must be related to the total quantity of evaporating liquid. The desired relation can be established as follows:

According to [3], the evaporation rate for a single particle is

$$\frac{dm}{d\tau} = -2\pi d_d \rho_{\mathrm{mix}} D_v \ln \frac{1 - C_\infty}{1 - C_0} [1 + 0.255\varphi \sqrt{\mathrm{Re}}], \qquad (6)$$

where $\varphi = f(C_0, C_\infty, \mathrm{Nu})$. Equation (6) is represented in a form more convenient for numerical computations:

$$\Delta m = \left\{ \frac{-2\pi d_d \rho_{\mathrm{mix}} D_v}{W_d} \ln \frac{1 - C_\infty}{1 - C_0} [1 + 0.255\varphi \sqrt{\mathrm{Re}}] \right\} \Delta l. \qquad (7)$$

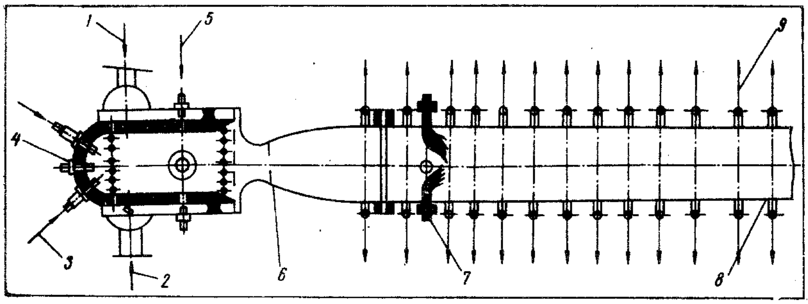

Fig. 1. Schematic diagram of the test apparatus: 1) oxygen; 2) air; 3) starting fuel; 4) spark plug; 5) fuel; 6) nozzle; 7) sprayer; 8) cylindrical tube; 9) to the manometers.

Assuming ρ_{mix}, D_V, C_∞, C_0, and φ to be constant for all droplets, we find the ratio $\Delta m_i/\Delta m$ with Δm_i denoting the quantity of evaporating liquid among m droplets of diameter d_{di} in the i-th category and Δm denoting the total quantity of evaporating liquid, calculated for segment dl of the channel,

$$\left(\frac{\Delta m_i}{\Delta m}\right)_{\text{calc}} = \frac{\sum\limits_1^m \frac{d_{d_i}}{W_{d_i}}\left(1 + 0.255\varphi\sqrt{\text{Re}_i}\right)}{\sum\limits_1^n \sum\limits_1^m \frac{d_{d_i}}{W_{d_i}}\left(1 + 0.255\varphi\sqrt{\text{Re}_i}\right)}. \tag{8}$$

From here, the actual quantity of evaporating liquid in the i-th category of droplets m becomes

$$\Delta m_i = \left(\frac{\Delta m_i}{\Delta m}\right)_{\text{calc}} \Delta m_{\text{exp}} \tag{9}$$

and the relative change in diameter of the i-th category within segment dl

$$\frac{\Delta d_{\text{d}}}{d_{\text{d}}} = \frac{1}{3} \cdot \frac{\Delta m_i}{m_i}. \tag{10}$$

dF/F the increment of cross-section area in the channel.

$d\mu/\mu$ is the relative increment of molecular weight, a parameter which is determined uniquely by the rates of phase and chemical transformations, i.e.,

$$\frac{d\mu}{\mu} = f\left(\frac{dm_{\text{evap}}}{m};\ \frac{dm_{\text{chem}}}{m};\ T\right). \tag{11}$$

Based on all this, the method of determining the rates of phase and chemical transformations in the stream was implemented as follows.

The experiments were performed on an apparatus suitable for operating with cold air (mode A), with a hot chemically inert gas comprising the products of kerosene combustion in air at $\alpha = 1$ (mode B), and with a hot chemically active gas comprising the products of kerosene combustion in gaseous oxygen at $\alpha = 1.2$-1.4 (mode C). The gas was accelerated to supersonic velocity through a Laval nozzle section terminating into a cylindrical tube (Fig. 1). Near the entrance, a set of spray needles for injecting the liquid was installed in the tube so that the liquid could be infused uniformly across the tube. The tube was drained throughout its entire length for measuring the static pressure of the stream.

The actual experiment was performed in the following sequence:

1. The flow in the tube was studied in all modes of operation without spray needles and liquid injection, in order to establish accurately the values of the friction coefficient for the given tube.
2. The effect of spray needles obstructing the flow (without liquid injection) was established by a blow test. An evaluation of this effect was based on the magnitude of the pressure recovery coefficient.
3. On the premise that the measured and the calculated pressure change in the tube due to the infusion of injected liquid must be made to agree, the dispersion characteristics of the injection

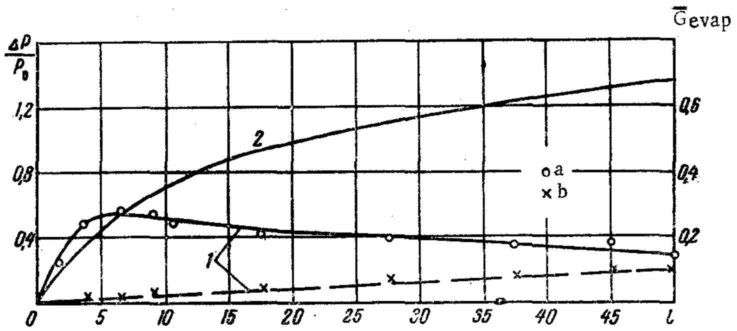

Fig. 2. Pressure distribution $\Delta P/P_0$ (1) (test values: with injection (a), blow without injection(b)) and calculated distribution of evaporated liquid mass $\bar{G}_{evap} = G_{evap}/G_j$ (2) with water injection throughout the apparatus length l (cm). $\bar{G} = 0.38$, $M_0 = 2.48$, $T_0^* = 1600$°K, $P_0 = 0.4$ bar, operating mode B.

system of spray needles in the path of a supersonic stream were determined by a blow test in mode A. The empirical constants in the formulas for calculating the dispersion spectrum and the ballistics of droplet motion in the given apparatus were determined at the same time.

4. After completion of steps 1-3, it is possible to calculate the effect of friction, the acceleration of evaporating droplets, and the presence of spray needles on the gas stream and, thus, only the effects of evaporation remain unknown. The evaporation rate is determined uniquely by adjusting the value of $\Delta m_{evap}/m$ for segment dl till the calculated pressure change $(\Delta P/P)_{calc}$ and the tested pressure change $(\Delta P/P)_{exp}$ agree completely.
5. Steps 1-4 are preliminary for determining the combustion rate (complete combustion). The evaporation rate must have been determined here either experimentally (steps 1-4) under conditions approaching those of the combustion process, or by calculations based on existing methods and corrected to account for the test conditions according to procedure 1-4. In the latter case the rate of fuel combustion remains the only unknown quantity, to be determined analogously to the evaporation rate in step 4.

In accordance with the sequence just described, we have developed a computer technique of processing the data of each step. From the initial values for the stream and the injected liquid and from the test results (pressure distribution in the tube), the computer yields the end values for each stage: the evaporation and the combustion rates along the channel. With data on the flow velocity along every tube segment already given, these results can easily be converted into respective process rates as functions of time.

To illustrate the applicability of this method, we show here actual test results: evaporation rates in a supersonic high-temperature water jet (approximately a 1:3 mixture ratio) in Fig. 2 and combustion rates for injected kerosene in Fig. 3. The water evaporation rates and the kerosene combustion rates shown on these diagrams have been obtained by recalculation in accordance with the pressure-change technique described earlier. Pressure measurements with and without attendant evaporation and combustion are also indicated on these diagrams.

On the basis of this example, with the results shown here, it is possible to evaluate – at least approximately – the accuracy of determining the rates of phase and chemical transformations by this method.

The accuracy of such a determination depends on the mathematical errors in converting pressures along the tube to process rates, on the errors in measuring pressure changes, and on errors due to various effects that have not been taken into account (wave effects during liquid injection and nonuniformities of flow parameters in the tube) on the pressure changes.

In the process of computer operations, these errors can be reduced to any desirable level. The error in plotting a pressure-change profile along the tube $\delta_{\Delta P}^{meas}$ can be reduced by modern techniques to ± 0.3-0.5%. Special numerical–theoretical and experimental studies have shown that, as a result of shock waves generated during liquid injection and of flow nonuniformities in the tube, the pressure curve may contain possible errors $\delta_{\Delta P}^{loss}$ of up to ±2-5% relative to the real effects of phase and chemical transformations.

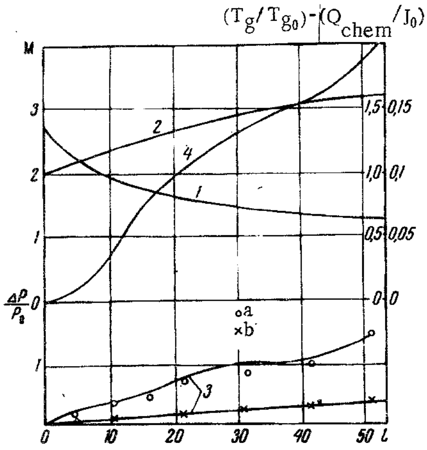

Fig.3. Change in flow parameters: M(1), T_g/T_{g0} (2), $\Delta P/P_0$ (3) (test values: with injection (a), blow without injection (b)) and relative quantity of released heat Q_{chem}/I_0 (4) during kerosene injection. $\overline{G} = 0.1$, $M_0 = 2.5$, $T^* = 1850$°K, $P_0 = 0.4$ bar, operating mode B.

Considering that friction plays a small role in the total pressure change during intensive phase and, especially, chemical transformations and that the injected liquid is accelerated, as a rule, over a short segment of the tube, these errors may be disregarded in an analysis of evaporation and combustion. Then, the relative error in the evaporation rate

$$\overline{\delta}_{evap} = \frac{\delta\left(\dfrac{\Delta m_{evap}}{m_j}\right)}{\dfrac{\Delta m_{evap}}{m_j}} = \frac{\delta_{evap}}{\Delta m_{evap}/m_j}$$

is determined according to the formula

$$\overline{\delta}_{evap} = \pm\left[(1-M^2)\,\delta_{\Delta P}\right] \Big/ \left[kPM^2\left\{y\left[1+(k-1)M^2\right]-\left(1+\frac{k-1}{2}M^2\right)\right.\right.$$
$$\left.\left.\times\frac{L_{evap}}{c_pT^*}-2\left(1-\frac{k-1}{2}M^2\right)\right\}\frac{\Delta m_{evap}}{m_j}\cdot\frac{m_j}{m}\right],$$

based on Eq.(1), where $\delta_{\Delta P}$ is the total absolute error of pressure measurements:

$$\delta_{\Delta P} = \pm\sqrt{(\delta_{\Delta P}^{meas})^2 + (\delta_{\Delta P}^{poss})^2}.$$

Inserting here the parameter values which correspond to our test conditions, we obtain

$$\overline{\delta}_{evap} \approx \pm\, 3 - 7.5\%.$$

When combustion is intensive, the evaporation of the burning liquid plays a less significant role in the total pressure change and – to the first approximation – its error may also be neglected. Then, by analogy, the relative error in the combustion rate

$$\overline{\delta}_{chem} = \frac{\delta\left(\dfrac{\Delta m_{chem}}{m_j}\right)}{\Delta m_{chem}/m_j} = \frac{\delta_{chem}}{\Delta m_{chem}/m_j}$$

is determined according to the formula

$$\overline{\delta}_{chem} = \pm\frac{(1-M^2)\,\delta_{\Delta P}}{kPM^2\left(1+\dfrac{k-1}{2}M^2\right)\dfrac{Q_{chem}(\alpha,\,T)}{c_pT^*}\cdot\dfrac{\Delta m_{chem}}{m_j}\cdot\dfrac{m_j}{m}}$$

and for our particular test condition it is

$$\overline{\delta}_{chem} = \pm\, 1.0 - 2.5\%.$$

A more precise analysis with a consideration of all accompanying processes will yield an error of up to ±8% in the evaporation rate and ±3-4% in the combustion rate, which should be entirely adequate for the solution of engineering problems.

NOTATION

M	is the Mach number;
Re	is the Reynolds number;
Nu	is the Nusselt number;
We	is the Weber number;
P	is the pressure
T	is the temperature;
F	is the area;
l	is the length;
D	is the tube diameter;
m	is the mass;
k	is an adiabatic exponent;
μ	is the molecular weight;
W	is the velocity;
c_p	is the specific heat at constant pressure;
Q	is the quantity of heat;
I	is the enthalpy;
L	is the heat of evaporation;
α	is the air excess;
ξ	is the coefficient of friction;
ρ	is the density
σ	is the coefficient of surface friction;
D_v	is the diffusivity;
C	is the vapor concentration;
G	is the flow rate (per second);
τ	is the time;
d	is the diameter.

Subscripts

calc	denotes calculated values;
exp	denotes experimental values;
chem	denotes chemical reaction;
evap	denotes evaporation;
cool	denotes cooling;
mix	denotes the mixture;
d	denotes droplet;
v	denotes vapor;
g	denotes gas;
j	denotes parameters of the injected liquid;
0	denotes zero cross section;
*	denotes stagnation parameters;
$0, \infty$	denotes vapor parameters, on the surface of the evaporating drop and in the stream, respectively.

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