Journal of Engineering Physics and Thermophysics, Vol. 72, No. 2, 1999

LAG IN THE TEMPERATURE MEASUREMENT SYSTEM IN PERFORMING FRACTIONAL DISTILLATION OF PETROLEUM PRODUCTS

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UDC 66.045.2

We carried out mathematical simulation of the temperature measurement system in performing fractional distillation of petroleum products (FDPP). To evaluate the actual lag in measuring the temperature in the process of FDPP, a special experiment was run on the basis of the mathematical model developed. It is shown that under unsteady-state conditions the error of a glass thermometer due to the phenomenon of thermal response may attain 15–25°C or more.

Fractional distillation is one of the most widely used methods of quality control of petroleum products, since it is a natural characteristic of mixtures that boil off in a certain interval of temperatures. The method known in worldwide technological practice as the ASTM D-86 technique involves measurement of the boiling-off temperature of the fractions of petroleum products from 0 to 1.

We developed [1] a mathematical model of fractional distillation of petroleum products. The FDPP curve can be described by the equation

$$v = \frac{a\tau^k}{1 + a\tau^k} . \tag{1}$$

The parameter τ is given by the formula

$$\tau = \frac{T - T_{\text{s.b}}}{T_{\text{e.b}} - T} .$$

Thus, FDPP can be characterized by four parameters: a, k, $T_{\text{s.b}}$, and $T_{\text{e.b}}$, for whose determination several techniques have been developed by us [2].

An important property of FDPP that is needed for solving various technological problems is the additivity of its integral characteristics [3].

In performing FDPP in accordance with the State Standards GOST 2177-82 [4] TN-7 glass thermometers were used that corresponded to the State Standards GOST 400-80. When measuring temperature in the vapor of boiling water under steady-state conditions, they can read values from 99.5 to 99.9°C, which is within the deviations indicated in the thermometer certificate (0.1–0.5°C).

In performing FDPP under dynamic conditions, the deviation of the temperature of the medium from that recorded by the thermometer can attain 25°C (this will be shown below). The lag in the temperature measurement system is due to the phenomenon of thermal response.

As is known [5, 6], the error in measuring a temperature under unsteady-state conditions is given by the formula

$$\Delta\Theta = b\varepsilon . \tag{2}$$

Polotsk State University, Novopolotsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 72, No. 2, pp. 240-244, March-April, 1999. Original article submitted February 14, 1997; revision submitted June 29, 1998.

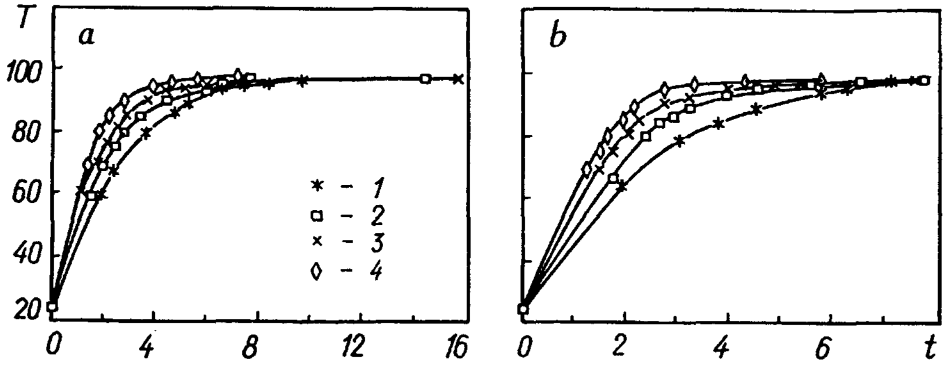

Fig. 1. Temperature T versus time t for main (a) and control (b) thermometers placed in the vapor of boiling water at a voltage across the laboratory transformer of: 1) 120 V, 2) 130, 3) 140, 4) 240.

To take account of this error, we carried out simulation of a system for measuring a temperature by a glass thermometer.

The thermometer can be treated as a combination of two systems: the glass body of the thermometer and the mercury cylinder. Taking this into account, we write an equation for the dynamics of the thermometer:

$$\frac{V_{\text{mer}}C_{\text{mer}}\rho_{\text{mer}}}{\lambda' F_{\text{mer}}}\,\frac{V_gC_g\rho_g}{\alpha_gF_g}\,\frac{d^2z}{dt^2}+\left[1+\frac{V_{\text{mer}}C_{\text{mer}}\rho_{\text{mer}}}{V_gC_g\rho_g}\left(\frac{\alpha_gF_g}{\lambda' F_{\text{mer}}}+1\right)\right]\frac{V_gC_g\rho_g}{\alpha_gF_g}\,\frac{dz}{dt}+z=0\,, \qquad (3)$$

where

$$z=\frac{\alpha_gF_g}{V_gC_g\rho_g}(T_{\text{mer}}-T_v)+\Sigma\,\Pi\,;\quad \lambda'=\frac{\lambda_g}{\Delta}\,.$$

Equation (3) is linear and homogeneous; its solution has the form

$$T_{\text{mer}}=\frac{T^{i}_{\text{mer}}-T^{f}_{\text{mer}}}{1-\dfrac{s_1}{s_2}}\left[\exp(-s_1t)-\frac{s_1}{s_2}\exp(-s_2t)\right]+T^{f}_{\text{mer}}\,. \qquad (4)$$

To determine the temperature of the mercury at any instant of time, it is necessary to know the roots of the characteristic equation s_1 and s_2. They depend on the geometric dimensions of the thermometer and its elements, the physical properties of the thermometer and the environment, the heat transfer from the environment to the thermometer, and so on.

To find s_1 and s_2 and eliminate errors in their calculation, a special procedure was developed that was preceded by the following experiment. In accordance with the State Standards GOST 2177-82, distillation of water was carried out in the apparatus at different voltages across the laboratory transformer (120, 130, 140, and 240 V). We used water for the experiments, because petroleum products are complex mixtures that do not have a constant boiling point. Under these conditions, the thermometer of interest was placed in a flask with boiling water, and data on the rate of rise of the temperature to 98–100°C were recorded. The experiments were carried out for two thermometers: the main one and a control. Both conformed to the same State Standards and had slight differences in geometric characteristics. The curves presented in Fig. 1 made it possible to recover the true distillation without any other evaluations or calculations. We will show this.

From an analysis of the experimental data it follows that the position of the inflection point on the curve of $T = f(t)$ is close to the coordinate origin, i.e.,

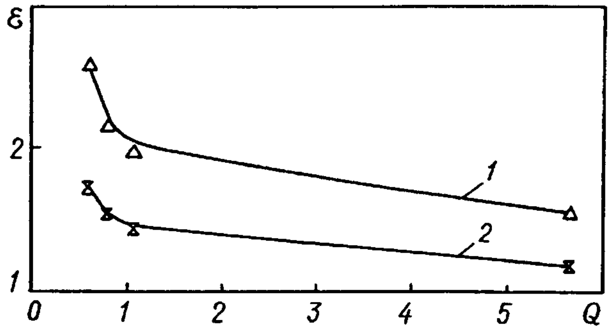

Fig. 2. Inertia ε of main (1) and control (2) thermometers versus the flow rate Q of steam. ε, min; Q, liter/min.

$$t = \frac{1}{s_2}\,\frac{\ln (s_1/s_2)}{\dfrac{s_1}{s_2} - 1} \to 0 .$$

This means that $s_1 >> s_2$, and expression (4) takes the form

$$T_{\text{mer}} = (T^{\text{i}}_{\text{mer}} - T^{\text{f}}_{\text{mer}}) \exp (- s_2 t) + T^{\text{f}}_{\text{mer}} ,$$

and the inertia

$$\varepsilon = s_2 = \frac{\left(\dfrac{dT_{\text{mer}}}{dt}\right)_{t=0}}{T^{\text{f}}_{\text{mer}} - T^{\text{i}}_{\text{mer}}} \tag{5}$$

can be determined from the curve of $T = f(t)$.

Using Eq. (2), for the main and control thermometers we may write

$$\Delta\Theta_{\text{m}} = b\varepsilon_{\text{m}} ; \quad \Delta\Theta_{\text{c}} = b\varepsilon_{\text{c}} ,$$

whence for $b \approx$ const

$$\Delta\Theta_{\text{m}} - \Delta\Theta_{\text{c}} = b\,(\varepsilon_{\text{m}} - \varepsilon_{\text{c}}) = b \left(1 - \frac{\varepsilon_{\text{c}}}{\varepsilon_{\text{m}}}\right) \varepsilon_{\text{m}} .$$

Then, the sought value of the lag of the main thermometer is

$$\varepsilon_{\text{m}} = \frac{\Delta\Theta_{\text{m}} - \Delta\Theta_{\text{c}}}{b\left(1 - \dfrac{\varepsilon_{\text{c}}}{\varepsilon_{\text{m}}}\right)} ,$$

where $\Delta\Theta_{\text{m}} - \Delta\Theta_{\text{c}}$ is the difference in the readings of the two thermometers for the same fraction of the distilled petroleum product, °C.

We assume that at the same rates of vapor the ratio of the inertias $\varepsilon_{\text{c}}/\varepsilon_{\text{m}}$ for steam is approximately equal to that for the petroleum product.

For the main and control thermometers we constructed a graph of their inertia (according to Eq. (5)) versus the steam flow rate (see Fig. 2). We take from this graph the ratio of the inertias of the thermometers for corresponding rates of the vapor of the petroleum products to calculate the lag in the readings of the thermometer.

Thus, to determine the lag temperature of the main thermometer it is necessary to have: 1) a graph of the inertia of the main and control thermometers versus the flow rate of steam; 2) data on fractional distillation of the

TABLE 1. Parameters of Fractional Distillation of Kerosene

Method of determination	a	k	$T_{\text{s.b}}$	$T_{\text{e.b}}$
With account for:				
the ratio of the inertias of two thermometers	1.67	1.10	168	269
the inertia of one thermometer	2.40	1.20	163	266
Without account for the inertia of the thermometer	1.08	1.52	140	245

same product carried out using these thermometers; this makes it possible to determine $\Delta\Theta_m - \Delta\Theta_c$ at each point of the distillation.

The variability of the lag in the readings of the thermometer behind the temperature of the medium at different points of the fractional distillation is readily apparent from its substantially nonlinear character and the fact that the FDPP is carried out relatively uniformly.

The inertia varies insignificantly within the limits of a specific distillation. Consequently, the lag in the readings of the thermometer is proportional to the rate of temperature rise in the object.

We can write

$$b = \frac{dT}{dt}\frac{dv}{dv} = \frac{dT}{dv}\frac{dv}{dt}.$$

If $dv/dt = \text{const}$ (according to the conditions of fractional distillation in accordance with the State Standards apart from the start and the end, when the process is slower), then, having differentiated Eq. (1), we obtain

$$\frac{dT}{dv} = \frac{T_{\text{e.b}} - T_{\text{s.b}}}{ak}\frac{(1 + a\tau^k)^2}{\tau^{k-1} + 2\tau^k + \tau^{k+1}}, \tag{6}$$

i.e., dT/dv changes substantially when $0 < t < \infty$.

From relation (6) it follows that $dT/dv \to \infty$ when $t \to 0$ and $t \to \infty$. Here $dv/dt \neq (\Delta v/\Delta t)_{\text{av}}$ and it tends to 0. In this case, b tends to indeterminacy, i.e., using Eq. (6), it is possible to find b for $0 < t < \infty$.

Let us consider another method of determining the lag in the readings of a thermometer.

Based on observed readings of the thermometer, in a first approximation we determine the parameters of fractional distillation a, k, $T_{\text{e.b}}$. The value of ε is taken from a graph (see Fig. 2) for the conditions of distillation on the specific thermometer. We calculate dT/dv from Eq. (6) along the entire curve of distillation, and we take $dv/dt \approx \Delta v/\Delta t$ from the averaged data for the entire process of distillation. We determine the lags $\Delta\Theta$, which have an extremal dependence with a minimum value $\Delta\Theta_{\text{min}}$ in the middle portion of the curve.

The parameters of fractional distillation of kerosene determined with account for the inertia of the thermometer by the two variants and without it are presented in Table 1. As is seen from the table, account for the inertia leads to a substantial and characteristic change in the parameters of the fractional distillation of kerosene that were calculated by the two methods, which in turn shows the validity of the assumption of the approximate equality of the inertia ratios of thermometers for steam and a petroleum product.

Thus, it is established theoretically and experimentally that there is an appreciable dynamic error in the measurement of temperature in carrying out fractional distillation of petroleum products in accordance with the State Standards GOST 2177-82. It is shown that, with all other things being equal, the value of this error changes both in the course of the distillation itself and with the characteristics of the petroleum product (the FDPP model).

The foregoing data indicate that by using inertialess heat receivers it is possible to obtain true temperatures, knowledge of which acquires special importance in solving technological problems on the basis of the additivity of the integral characteristics of FDPP and in creating a computer complex for analyzing petroleum products on the

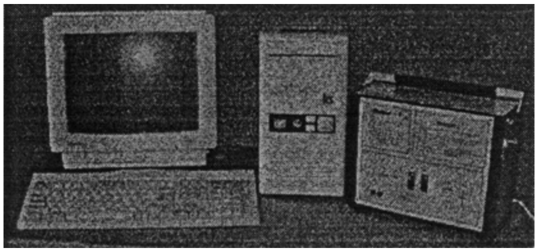

Fig. 3. Computer complex for simulating the properties of petroleum products on the basis of fractional distillation.

basis of FDPP data. This will make it possible to exclude the use of approximate methods of taking account of the inertia of thermometers.

On the other hand, account for the inertia of the temperature measurement system or creation of a low-inertia system will make it possible to accelerate the process of FDPP and retain, by means of recalculation, the possibility of obtaining data in accordance with the State Standards GOST 2177-82. The results of simulation of the inertia of a heat receiver in carrying out FDPP were used by us in creating the "Polotsk-1" computer complex (see Fig. 3), which makes it possible to conduct accelerated fractional distillation of white petroleum products in several minutes. The complex incorporates a virtually inertialess system for measuring temperature and the results of the present work for conversion of results of measurements into data that correspond to the State Standards GOST 2177-82. The computer complex makes it possible not only to carry out accelerated FDPP but also, using the capabilities of the modern computer and the algorithms developed, to solve various analytical and technological problems in petroleum refining and related areas on the basis of the simulation of FDPP. Preparation is underway for commercial production of "Polotsk" computer complexes by the "Izmeritel'" factory (the town of Novopolotsk).

CONCLUSIONS

1. We carried out simulation of the temperature measurement system in conducting fractional distillation of petroleum products.

2. It is shown that under standard dynamic conditions the error in measuring the temperature in the process of FDPP by a TN-7 glass thermometer may attain 15–25°C or more.

3. Two methods of determining and accounting for the lag in the readings of the thermometer in the course of FDPP are proposed.

4. Knowledge of accurate values of temperature under dynamic conditions is of fundamental importance in solving problems on the basis of the simulation of FDPP and in creating a computer complex for analyzing petroleum products using a low-inertia system of measurement.

NOTATION

a, symmetry index of the FDPP curve for $\tau = 1$; b, rate of change of the temperature in the object, °C/unit of time; C, heat-capacity coefficient, J/(kg·K); F, surface area, m^2; k, index of the intensity of the FDPP for $\tau = 1$; $\Sigma\Pi$, heat losses, W; T, temperature, °C; t, time, sec; Δt, change in time, sec; V, volume, m^3; α, heat-transfer coefficient, W/(m^2·K); Δ, thickness of the glass wall of the thermometer body, m; ε, inertia of the system, units of time; λ, thermal conductivity, W/(m·K); ν, fraction of distilled petroleum product, volumetric; $\Delta\nu$, change in the fraction of distilled petroleum product, volumetric; ρ, density, kg/m^3; τ, dimensionless parameter; $\Delta\Theta$, lag in the readings of the thermometer, °C. Superscripts: i, initial; f, final. Subscripts: s.b and e.b, start and end of boiling of a petroleum product; mer, mercury; g, glass; av, averaged; m, main; c, control; v, vapor of a petroleum product.

REFERENCES

1. I. A. Dimudu, O. N. Jarkova, and G. N. Abaev, Inzyneria Chemiczna i Procesova, 17, No. 4, 635-644 (1996).

2. I. A. Dimudu, O. N. Zharkova, G. N. Abaev, and A. V. Spiridonov, Izv. VUZov, Khim. Khim. Tekhnol., 38, Nos. 1-2, 136-142 (1995).
3. O. N. Zharkova, I. A. Dimudu, G. N. Abaev, and A. V. Spiridonov, Khim. Tekhnol. Topliv Masel, No. 5, 38-40 (1995).
4. State Standards GOST 2177-82. Petroleum Products. Methods for Determining Fractional Composition.
5. G. M. Kondrat'ev, Thermal Measurements [in Russian], Leningrad (1957), pp. 52, 55.
6. V. G. Dianov, Technological Measurements and Instrumentation for Chemical Production [in Russian], Moscow (1973), p. 206.