Garris N., Garris Yu.

Ufa State Petroleum Technological University, Ufa

DYNAMIC CHARACTERISTIC APPLICATION IN OPERATING CONDITIONS CALCULATION OF MAIN NON – ISOTHERMAL OIL – PRODUCT PIPELINES

INTRODUCTION

Higher requirements are made to the calculation quality of main non-isothermal oil-product pipelines operating conditions, while transferring various oils and oil-products at the ambient temperatures, high viscosity and shear stresses occur and involve excessive power to overcome a pipeline hydraulic resistance. The thixotropic properties exclude pumping shut down possibility for a long time. Heat required for "hot" pumping varies within the year: in summer less heat is used for warming up as compared to that in winter. So pipeline heat-hydraulic conditions are variable during the year. Besides the capacities of centrifugal pumps (CFP) and heater vary within the year due to technological causes including scheduled and emergency shut downs. The designed stationary condition is hardly ever achieved in non-isothermal pipelines, so the pipelines seldom operate in the designed conditions, working at underloading.

OPERATING CONDITIONS

Currently available methods of calculation of non-stationary operating conditions for non-isothermal pipelines make it possible to calculate the above processes only approximately within a specific range of accuracy. This is due to the complexity of the associated phenomena and branch standard fail to account for the change of pump capacity Q as a result of change of pump hydraulic resistance in non-isothermal non-stationary processes. Fluctuations in pump capacity and temperature of he pumped fluid are interconnected. That is why the regularity Q = const is true only for reciprocating pumps.

At prolonged operation of CFP on a "hot" pipeline (see fig.) the operating parameters of the system are defined by intersection point A of stationary curve of a "hot" pipeline I with pump curve. In non-stationary operation the working condition is defined by intersection of instant curve and pump curve, i.e. B_i. By instant curve is meant graphical relationship between head loss and fluid flow in the pipeline at the given moment. This characteristic is isothermal. The fluid flow in the pipeline being changed with time as the result of hydraulic resistance change, work point B_i will move along the CFP curve, approaching point A under heating, and point C under cooling, setting the capacity to"0" (point D).

The development of similar processes depends on two factors: the pump characteristic steepness and the ground thermal inertia which defines the rates of pipeline heating up and cooling.

The pipeline system operational practices show that "hot" main pipelines operate in non-stationary conditions, with complicated stratum of "background" of pump switchings, shut downs and resumptions. This leads to the fact that theoretically within a year there are no uniform temperature fields around the pipe. Abundant control evidence testifies that very often the values of hydraulic loss **h** in the pipeline and temperatures t_{in} and t_{out} do not correlate (t_{in} and t_{out} are temperatures of the fluid pumped at input and output sections of the pipelines). Usually that is attributed to inaccurate measurement and experimental errors. But there may be another explanation and a quite definite one.

Due to the ground thermal inertia, conditions change, accompanying by the variation of the specific thermal flow into the ground, different processes can proceed at various distances off the pipe. For example, as a result of abrupt temperature decrease during pumping, there will begin cooling in the adjacent layer of the ground while at a distance heating up will continue. This is explained by the fact that as a result of thermal inertia of the ground the disturbance wave will reach remote areas only in some period of time. But before that the "previous" heating up will continue at the periphery. And so on. With every change a wavy "accretion" of the action goes on both along the pipeline and in cross-sections, i.e. about the tract. We note, that those transformations are not sharply defined. Nevertheless all that essentially reflects on non-stationary heat emission efficiency K_τ, which at the same thermal head t_{av}-t_0 may differ greatly from stationary one (t_{av} – is averaged product temperature per a section length; t_0 - is temperature of the ground at a depth the pipeline is imbedded in a non-disturbed thermal conditions, or asymptotic temperature). As K_τ is involved in the formulas for calculation of hydraulic loss, the apparent inconsistency between loss **h** and thermal condition t_{in} and t_{out} become clear. The same is true for thermal flow **q .**

In the ground very complicated redistribution of not only temperatures but humidity as well takes place. The values of thermal and mass transfer efficiency have hardly ever been determined in such cases.

In addition to the above reasons the operation of pipeline systems is influenced by climatic conditions emerging as extreme conditions connected with sharp ambient temperature changes, plentiful precipitation, floods, drought, etc., which change the nature of heat exchange greatly, thus the hydraulic resistance as well, and, as a result, disrupting the pump capacity.

The centrifugal pump capacity decreases with a rise of hydraulic resistance of the pipeline, the rate of decrease thereof depending on the steepness of the CFP' s characteristic. The capacity decrease results in excess cooling and temperature drop as the fluid moves to the terminal point of the pipeline. The drop of pump capacity continues till complete suspension of discharge and "freezing" the pipeline unless special measures are undertaken.

PROBLEM STATEMENT

If we consider that a parameter like pipeline capacity is determined not only by its hydraulic resistance but the pumping equipment resource as well, see point A in the figure, then the necessity of taking into account pumping characteristic (5) in the set of differential equations (1-7) describing non-stationary processes under corresponding extreme conditions and common assumption, is obvious:

- of movement

$$\frac{\partial(\rho\cdot\upsilon)}{\partial\tau}+\frac{\partial}{\partial z}(p+\rho\cdot\upsilon^2)=-\rho\cdot g\cdot\sin\alpha+\frac{2\cdot\tau_{fr}}{R}, \quad (1)$$

- of continuity

$$\frac{\partial \rho}{\partial \tau} = -\frac{\partial(\rho \cdot \upsilon)}{\partial z}, \quad (2)$$

- of energy

$$\frac{\partial t}{\partial \tau} + \upsilon \cdot \frac{\partial t}{\partial z} = \frac{2 \cdot \pi \cdot R \cdot q(t)}{\rho \cdot c \cdot F} + \frac{\upsilon}{c} \cdot \frac{dh}{dz}, \quad (3)$$

where: $$q(t) = \frac{\lambda_1}{2 \cdot \pi \cdot R} \int_0^{\pi} \left. \frac{\partial t_1}{\partial r} \right|_{r=R} dr, \quad (4)$$

- of centrifugal pumps

$$H_{,} = H' - k_0 \cdot Q^{b_0}, \quad (5)$$

- isolation conductivity

$$\frac{\partial t_i}{\partial \tau} = a_i \cdot \left(\frac{\partial^2 t_i}{\partial z^2} + \frac{1}{r} \cdot \frac{\partial t_i}{\partial r} \right), \quad (6)$$

$$R_i \le r \le R_{i+1}$$

- ground conductivity

$$\frac{\partial t_{gr}}{\partial \tau} = a_{gr} \cdot \left(\frac{\partial^2 t_{gr}}{\partial x^2} + \frac{\partial^2 t_{gr}}{\partial y^2} \right), \quad (7)$$

where: ρ, c, ν are density, heat capacity and fluid velocity through the pipeline, respectively; p and t are pressure and temperature, respectively; τ is time; R and R_i are radius of the pipeline and isolation, respectively; x, y, z are coordinates of pipeline' s axis; α– incidence angle of pipeline to horizon, τ_{fr} is shear stress on the wall of the pipe; q(t) is heat flow through the wall of pipe; F is area of the pipe' s cross-section; h is friction loss; H_p and H' are head of centrifugal pump at capacity Q and zero capacity, respectively; k_0 , b_0 are empirical coefficients in equation (5); t, t_1, t_i and t_{gr} are temperatures of the fluid, pipe wall, isolation and ground layers, respectively; λ_1, λ_i and a_i a_{gr} are coefficients of heat and temperatures conductivity, respectively.

So, another CFP' s characteristics equation (5) has been added to the very simple set of five differential equations describing hydrodynamic processes and heat exchange of underground pipeline. A connected problem in general way is presented by the set of equations (1-7), at corresponding extreme and adjacent conditions.

Solution of the given adjacent problem in general form seems to be impossible. Analytical solution of the equations set (1-7) is very hard, even with numerous assumptions. It is possible to simplify the approach to solve problems of the given class using method of consecutive change of stationary conditions.

This concept can be realized in analytical setting up with computerized and analytical- tabular methods. The achieved analytical solutions of defining the time of heating up the pipeline, the time of safe pumping shut down and soon, will be omitted as they are rather cumbersome, references being made to algorithms and corresponding computerized calculation programs for principal non-stationary processes. Let us consider the analytical-tabular method for solving adjacent problems using dynamic characteristics of pipeline system.

It should be noted that solution non-stationary heat conduction problems using dynamic characteristics, was begun in 1976 [1]. The method of dynamic characteristics has been successfully used for calculation of non-stationary conditions for Okha -on Sakhalin - Komsomolsk - on the Amur and Uzen – Shevchenko pipelines, calculation of the safe shut down time during transportation of Buzachian's oil, in residual fuel oil pipelines in Bashkortostan, etc. [2,3,4]. Solution of equations (1-4, 6-7) provides the amount of required head:

$$H = \frac{P_{out}}{\rho \cdot g} + \Delta z + h(t) = \Delta z' + h(t) \qquad (8)$$

for pumping the fluid through the pipeline in the thermal conditions defined by the heat inertia of the ambient tract, i.e. by differential equation (7). It is convenient to give the adjacent condition on the pipe contour by the thermal flow supposing heat exchange balance, for example, with equation:

$$q = Q \cdot \rho \cdot c \cdot \left(\frac{dt}{dz} \right)_R . \qquad (9)$$

Combined solution of equations (5) and (8) yield parameters of operating point at the moment under review: pumps capacity Q and head H developed by the pumps. For stationary conditions those are Q_A and H_A; for non-stationary conditions they are Q_{Bi} and H_{Bi}, see fig. Energy balance at the work point of the combined curve is:

$$h(t) + \Delta z' = H' - k_0 \cdot Q^{b_0} . \qquad (10)$$

It should be noted that the amount of energy loss h(t) for oil pipelines now in equation (8) can be determined with regard to actual hydraulic resistance.

Non-stationary work of the system can be considered as a process of transportation from one stationary condition to another. Conditions at non-stationary transitions are defined by instant characteristics moving about H-Q area of the pump, pump stationary characteristics being considered basic, denoting a stationary operating condition which the system tends to after any disturbance. That is why when defining the area of possible capacities $Q_{max} – Q_{min}$ it is necessary to consider the relative positions of pump characteristics and pipeline characteristics: stationary and instant ones.

The main point of the heat hydraulic calculation of warming up system is expressed by determining temperatures and derivation of instant characteristics for every instant moment of time on their basis. The required head is determined by intersection points B_i and compared to acceptable one. In a similar way the freezing temperature of the pumped oil and other factors are considered.

DYNAMIC CHARACTERISTICS OF A "HOT " PIPELINE FOR PUMPING VISCO-PLASTIC FLUIDS

A distinctive feature of the characterization of a pipeline for visco-plastic fluids transportation is that it starts not with zero but with some static head amount at zero capacity. When operating pumps at low capacities, the head losses in the pipeline consist of friction losses H_v and yield stress losses H_τ:

$$h(t) = H_\nu + H_\tau . \qquad (11)$$

Four typical regions can be formed along a non-isothermal pipeline, having different flow conditions and hydraulic resistance rules. The proposed STAS program accounts for such a version of calculation. The viscous friction loss is determined with regard to the flow non-isothermality across the section and along the length of the pipeline.

To define energy losses H_τ in view of temperature linear dependence τ_0 of form:

$$\tau_0 = \tau_0^* \cdot \frac{t_y - t}{t_y - t_0} \tag{12}$$

we suggest formula:

$$H_\tau = \frac{16 \cdot \tau_0^* \cdot L}{3 \cdot d \cdot Su} \cdot \left(\ln \frac{t_y - t_0}{t_{out} - t_0} + \frac{t_{in} - t_0}{t_y - t_0} - 1 \right), \tag{13}$$

where: $Su = \ln \dfrac{t_{in} - t_0}{t_{out} - t_0}$,

t_y is the temperature at which critical shear stress appears, τ_0^* is yield stress at temperature t_0; d and L are inner diameter and length of the pipeline, respectively.

STAS program also provides for calculation of energy losses H_τ if stress τ_0 is defined by exponential dependence:

$$\tau_0 = \tau_0' \cdot e^{-st} - y. \tag{14}$$

As the capacity increases the terminal fluid temperature increases also, and at $t_y \le t_к$ quantity H_τ=0. On the dynamic curve, see fig., curve II - H_τ=f(Q) dependence. Instant characteristics are also plotted. A special feature of the construction of an instant characteristic is that every time quantity H_τ corresponding to given average flow temperature t_{av} must be considered.

The figure shows construction of an instant characteristic, for example, for t_{av}=50°C. We draw a horizontal from the temperature axis to intersect curve t_{av} (III), and we get point n. From point n we drop a perpendicular to intersect curves II and I – we get point m, through which we draw an instant characteristic.

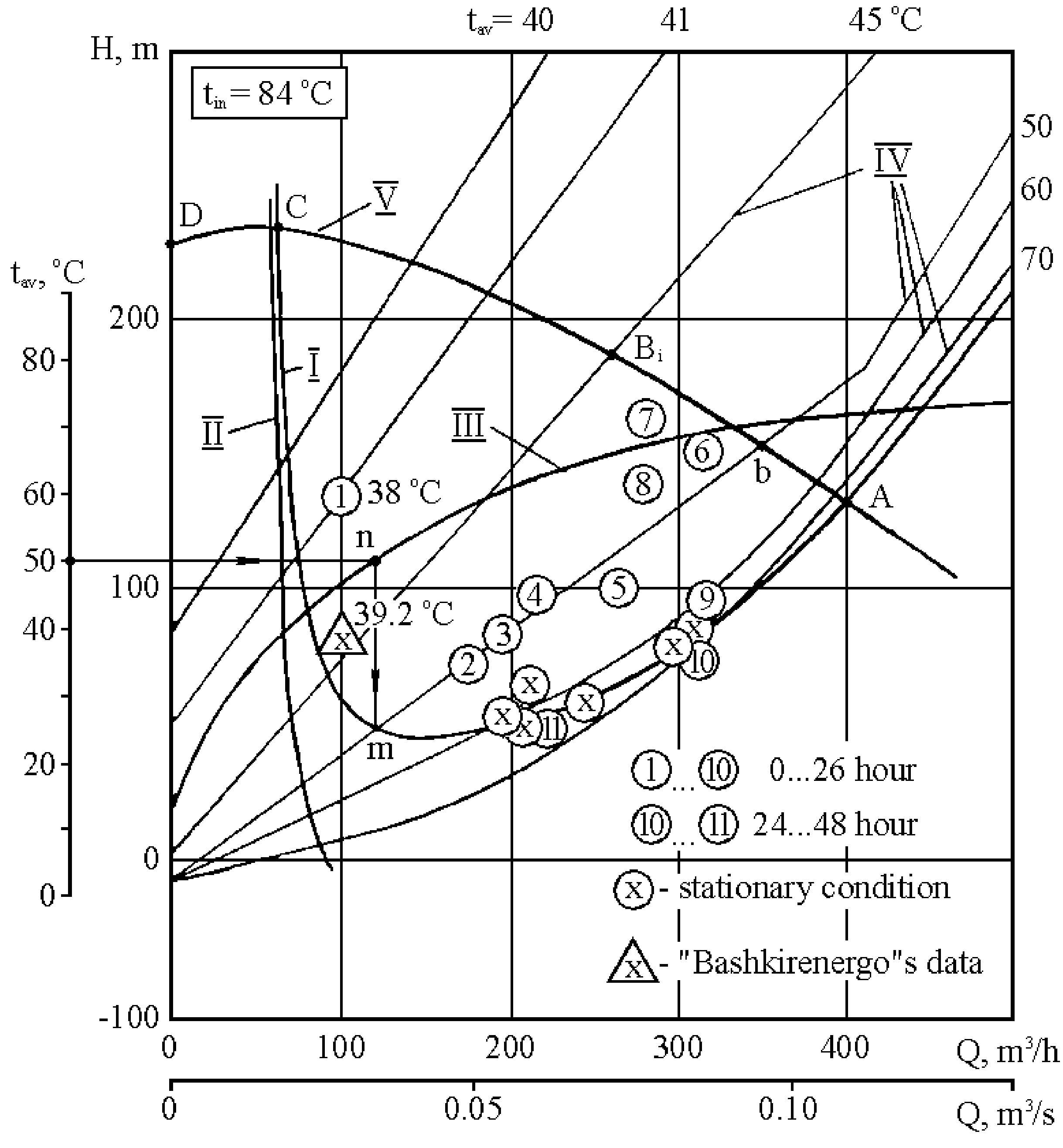
With a knowledge of the instant characteristic position, it is possible to determine pump operating parameter by point b: Q_b=350 m³/h and H_b=155 m for a given moment.

DYNAMIC CHARACTERISTICS OF "SNHK – STETZ" RESIDUAL FUEL OIL PIPELINE. INDUSTRIAL APPROVAL.

Method of dynamic characteristics has been approved at a number of industrial pipelines. The dynamic characteristics of "SNHK – STETZ" residual fuel oil pipeline designed for pumping M100 fuel oil with temperature t_{in}=84 ^oC, show a correlation with full-scale experiment data at the summer 1979, wich experiment was conducted to examine the shut down processes and following startup of pumping the fuel oil through the pipeline.

The shut down lasted for 12 hours. Before the experiment the ground had been well heated, because the fuel oil pipeline had worked under a stationary condition for a long period of time with Q=212 m^3/h and t_{in} = 85 ^oC. There are condition points on field Q – H, designated with numbers in the following order: at the “start-up” moment point 1, non-stationary state process development – points 2…8 and stationary condition – points 9…11.

Dynamic characteristic of "SNHK-STETZ" residual fuel pipeline



I – fuel oil pipeline required head curve;
II – static heads;
III – average temperatures curves;
IV – instant characteristics;
V – 8НД-9х3 pump perfomance.

Fig.

It is seen from the figure that in sprite of low rate Q=100 m^3/h at the "start-up" moment, the head losses in the pipeline are large and they are twice as much as those under a stationary condition. The reason is that by the moment pumping restarted the temperature of the fuel oil was measured t_{av} =38 ^oC. Since the parameters of point 1 correspond to the instant characteristic drawn for t_{av} =41 ^oC, relative error =(38-41)/38=-7,9%.

Beginning with the pump restart the fluid temperature increases quickly because the thermal inertia of the ground contributes to the restoration of the condition. The condition points are in the area of the instant characteristic at 50 ^oC, then 60 ^oC and finally they fall on the stationary characteristic of the fuel oil pipeline. After 26 hours from the pump restart, the position is at point 10, after 50 hours it is at point 11.

The points designated "x" correspond to stationary conditions, they are obtained as a result of long-term pipeline observations carried out during the period from the resumption of pumping in October, 1978, till 1983.

CONCLUSION

In conclusion it should be pointed out that the above method of dynamic characteristics suggested for calculation of stationary conditions of a "hot" main oil-products pipelines, has the following benefits over standard procedures based on flow constancy Q= const.

1. When calculating non-stationary operating conditions for a main pipeline the method of dynamic characteristics allows for changing the capacity of CFP with the change of the pipeline hydraulic resistance.
2. Changing capacity rates at start-up, heat-up, shut down and restart, drop of output, pipeline fluid temperature changes can be calculated with the above method, weather factors and so on being promptly considered.
3. The dynamic curve can be drawn up for any flow model fluid including thixotropic one. The more complicated the model is, the more substantial is the efficiency of the method.
4. The calculation algorithms for non-stationary conditions of oil-products pipelines using dynamic characteristics, can be realized with a computer. PROGR and BOST programs generated in OBJECT PASCAL language in DELPHI medium enable to determine not only heat-up time at pipeline start-up from cold condition and safe shut down time, but also start-up parameters for centrifugal during heat-up and at the resumption moment.

ACKNOWLEDGE

The organization support of JSC "Bashkirenergo" and USPTU colleagues in experiments on the fuel pipeline is gratefully acknowledged.

REFERENCES

1. N.A. Garris. Dynamic Characteristic Application in Thermal Hydraulic Calculation of Heating-up Underground Pipelines // RNTS BNIIOENG. Ser. Oil and Oil-products Transportation and Storage. 1976, №7, p.7-8

2. Calculation Procedure for Operating Conditions of Heat-insulated Fuel Oil Pipelines. "Glavneftesnab RF". Laboratory of pipeline transportation. – Ufa: UOI, 1976. –79p.

3. Thermal Hydraulic Calculation Procedure for Fuel Oil Pipelines. "Goskomnefteprodykt RF". Laboratory of pipeline transportation. - Ufa: UNI, 1982. - 55p.

4. P.I.Tugunov, N.A.Garris. Dynamic Characteristics Application in Operating Conditions Calculation for Non-isothermal Pipelines // Ser. Oil and Oil-Products Transportation and Storage. 1985, №3, 60 p.