Methodology of dynamic pumps testing on high-viscosity liquids

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Abstract. The article describes the experience of testing various types of dynamic pumps with high-viscosity liquids, both at low and at high temperatures of the operating environment. A systematization of possible methods for such tests operations and a comparative analysis of their advantages and disadvantages are given. Simplified schemes of test benches are given. Approximate limits of applicability of various methods are determined. The ways of solving the problems of hydrodynamic similarity adherence with these types of tests and such test benches development prospects are briefly proven.

1. Introduction
The problem of securing operation of dynamic pumps (rotary type, axial, disk pumps) with high-viscosity liquids (up to 3000cSt and more) is widely spread nowadays. Such pump operating conditions are typical for petroleum and chemical industries, food industry, in medical equipment and for thermostabilisation systems of different applications. In general, dramatically increasing working fluid viscosity causes dramatic drop in energy performance of dynamic pumps. Quick development of computational fluid dynamics allows to design, research and optimize pump design directly for high-viscosity liquids. These problems are described in papers [2-12]. However, high-viscosity testing of such pumps is a complex engineering and scientific problem. Solving it would require selecting a working liquid and designing the test bench capable of maintaining constant properties on the working medium. This paper is dedicated to analysis of possible test methods and means of dynamic pumps testing with high-viscosity liquid, based on previous testing experience of BMSTU and Central Research Institute of Automation and Hydraulics NPO Gidromash OJSC scientists.

2. Testing methods
The main similarity parameter on rotary pump tests is Reynolds number which for rotary pump is written for example as [13]

$$Re = \frac{\omega R^2}{v},$$
where
\[ \omega \] – rotor rotational speed, rad/s;
\[ R_2 \] – wheel output radius by stream tube, m;
\[ \nu \] – kinematic coefficient of viscosity, m\(^2\)/s.

During simulative pumps testing for abidance of similarity consideration it is important that Reynolds numbers for simulative and real pumps are be either equal (it’s usually unfeasible because of the dramatic difference between simulative and real pumps dimensions) either be within the frames of self-similarity [14].

For simulative and real pumps Reynolds numbers must be much greater than \(2 \times 10^6\) which is corresponds to pump operation within the frames of self-similarity [15-18]. More specifically, Reynolds numbers for vane pumps corresponding to start of the self-similarity frames, can be dramatically lower, because of the turbulizing factor in terms of rotating vane grid slightly change boundary-layer flow. However liquid viscosity increasing, for example from 200 to 2000 c St lead to Reynolds number changing inversely to liquid viscosity (in this case an order of magnitude). The similar problem appears in real pump testing in a wide range of viscosities, but in this case it should be noted that the self-similarity condition is violated in the same way as real pump self-similarity trouble similar with real operation condition troubles which is acceptable.

Otherwise, impact of scale effect on testing pumps models with high-viscosity working liquid is practically unexplored. The significant factor is the change of the flow pattern in real and simulative pumps flow section which is dramatically depending on the flow sections dimensions. Particularly, during testing pumps with low flow rate in altitude-temperature chamber (Central Research Institute of Automation and Hydraulics) for Reynolds numbers calculated for wheel rotating vane grid on the order of \(1 \times 10^3\) and for Reynolds numbers for flow in channels on the order of \(10^2\) was found out laminar flow regime of the liquid in the guide vanes channels.

A typical relationship between working liquid characteristics (kinematic coefficient of viscosity and density) and its temperature is presented in the figure 1. The example of dynamic pump characteristic change cause by increasing working liquid viscosity is presented in figure 2.

![Figure 1. The relationship between working fluid characteristic and temperature.](image-url)
Having analyzed both these charts it is now possible to formulate the following problems occurring during high-viscosity liquid dynamic pump testing.

1. According to pump operating mode in test bench (operating mode changing many fold during testing) its capacity and efficiency change. All the pump power input, except external mechanical losses (which are usually relatively insignificant) heat the working liquid in test bench. Hence, the pump in test bench is an unstable source of heat generation. In this case heating rate in test bench can be evaluated by the formula:

$$\tau = \frac{\Delta T \cdot V_l \cdot \rho \cdot C_v}{N_{heat}},$$

where

- $\tau$ – liquid heating rate in test bench, s;
- $\Delta T$ – temperature drop from the original to final condition, K;
- $V_l$ – total volume of the working liquid in the test bench, m$^3$;
- $\rho$ – liquid density, kg/m$^3$;
- $C_v$ – specific heat capacity of the working liquid, J/kg·K;
- $N_{heat}$ – heat generation capacity, which can be written as power input times the external mechanical efficiency of the pump, W.

1. Working liquid viscosity dramatically depends on the temperature, especially in the left part of diagram. Even negligible heating of the operating environment leads to decrease of the viscosity and in turn to change of the pressure head and efficiency changing.

2. Operating environment density is weakly dependent on temperature and it can be easily taken into account.

3. Gas content in the liquid will dramatically influence its viscosity. Deaeration of the operating environment in test bench is necessary. Based on testing experience, it’s a significant factor for high-viscosity liquids because it is difficult to deaerate all volume of liquid in test bench in this case. Usually lengthy operation of the test bench in recirculation mode is required.
Thus, in the system “test bench with high-viscosity liquid – pump with intermittent operation” complicated oscillating heating processes appear, which is influencing on the test process. Operating mode is changed – heat generation capacity is changed – working liquid viscosity is changed – operating mode is changed.

The ultimate aim is getting a variety of characteristic each of them has to be read in with fixed working liquid viscosity with fur there laboration and nondimensionalization and/or design equation. During operation the pump will be working in open-loop hydraulic system or in circulating system with rather huge amount of liquid.

3. Results

Testing pumps in test benches with high-viscosity working liquids were carried out in Russia in such organizations as the Central Research Institute of Automation and Hydraulics (with antifreeze agent in cooling chambers and with high-viscosity oils. Test are carried out by the authors), in BMSTU (with liquid mixtures contain emulsifiers and thickening agents. Test are carried out with the authors’ participation), in NPO Gidromash OJSC (with hydroglyceric solutions and oils) and in other organizations.

What solutions for solving the heat balance and liquid viscosity regulation problem in the “test bench – pump” system can be applied? Firstly, it is necessary to determine what working liquid viscosity characteristic area the test bench will be operated in. Two of applicable working temperature limits for extremely high-viscosity liquid $L_1$ at room temperature and for relatively low-viscosity liquid $L_2$ illustration is presented in the figure 3 (for example, $L_2$ is an oil, $L_1$ variable concentration guar gum aqueous solution).

![Figure 3. Example of different viscosity working liquid application ranges.](image)

Based on the example it can be concluded that the range of accepted temperatures $\Delta T_1$ for high-viscosity liquid in demanded range of viscosity $\Delta \nu$ is rather big, which allows to operate the test bench without high-accuracy temperature stabilization system.

The reverse side of this solution is impossibility of viscosity increasing or decreasing during operation. Such increasing can be achieved only by changing emulsifying agent concentration (in this case guar gum) by carefully stirring the liquid during test bench operation and consequent viscosity measurement of the obtained water solution.
On the other hand if we are working with a liquid that has a type L₂ relationship between viscosity and temperature in the temperature range ΔT₂, even negligible heat generation increase would lead to sudden change of the working liquid viscosity.

In this case an appropriate temperature range in very narrow, it requires extremely high-accuracy temperature stabilization system with high operation speed (to in time react for heat leak changing in pump operation changing).

This method allows changing the liquid viscosity in wide ranges by simply changing the temperature (by both cooling and heating) without changing its composition. It is difficult to calculate heating oscillatory processes in such test bench because of the effect of the variable pump operation mode, change of test bench heat generation to environment and nonlinearchange of the liquid flow pattern through the test bench parts.

In light of this, there are three of appropriate test benches designs for dynamic pumps with high-viscosity liquids and with different testing methodologies:

1. Test bench with thermostabilisation servosystem (cooling machine and heat-exchange unit are embedded, an additional heating system for L₂ working liquid, with working liquid temperature feedback and PID controller). Such scheme is presented in figure 4. For big pump testing thermostabilisation system is done as a separate unit with external circulation liquid circuitconnected to the tank. Vacuum system for working liquid deaeration is required too.

![Figure 4. Scheme of the test bench with working liquid thermostabilisation servo-mechanism.](image-url)
2. Test bench with huge amount of high-viscosity working liquid (like L1) and relatively low pump output what provides thermostabilisation by large temperature inertia (low heating rate) of the test bench, but at the same time is makes operation of the test bench more complicated because of the necessity to change supplemental additive concentration in a huge amount of the liquid. Working liquid amount in the test bench has to allow full testing without significant increasing the viscosity. It can be calculated based on the previous formulas and viscosity change diagram for the liquid.

3. Test bench operating on extremely high-viscosity liquid (type L1) with powerful unregulated heat-exchange unit (viscosity stabilisation provided by operation on the first stage of the viscosity characteristic) and with stepped variation of the emulsifying supplemental additive concentration. In addition, viscosity analyzer in test bench is required (figure 5).

**Figure 5.** Scheme of the test bench with extremely high-viscosity working liquid.

In case there is no possibility to implement thermostabilisation servo-mechanism to the test bench with L₂ working liquid it is possible to test pump with continuous rating [20], but it is very labor-intensive and lengthy method.

The example of the final dimensionless characteristic for the low specific speed rotary pump characteristic obtained using the proposed method is presented on figure 6.
4. Discussion

1. Possible testing methods of dynamic pumps with working liquids in huge range of viscosities presented in the paper are tested through practice and can be used the wide range of similar problems.

2. It is required to do additional research for studying similarity and scale effect during testing such pumps with high-viscosity liquids. Right now this research is carried out at Hydraulics department E10 of BMSTU.
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