OPERATION OF A THREE-SCREW PUMP ON DIESEL FUEL

V. M. Ryazantsev

The suction capacity of a three-screw pump has been considered in detail in [1, 2], where oil with viscosity 2–60·10⁻⁵ m²/sec was used. Here I describe experience with modifying three-screw pumps to provide the required vibrational and noise characteristics in pumping diesel fuel DF of viscosity 3–7·10⁻⁶ m²/sec, density ρ = 832 kg/m³, and vapor pressure pᵥ = 4900 Pa at 30°C. The main reason for the deterioration in the vibration and noise characteristics in pumping DF by comparison with those on oil (for equal vacuumetric lift heights) is cavitation. At 30°C, the vapor pressure of the oil was about 1000 Pa, so cavitation sets in at a greater lift. Also, the high viscosity of the oil delays the development of cavitation.

In calculations on cavitation in hydraulic machines, one usually takes the critical pressure at which cavitation begins as the saturation vapor pressure pᵥ at the working temperature. Cavitation involves the growth of very small bubbles filled with free gas or vapor from the liquid and existing in the liquid before the start of cavitation. Free-gas bubbles act as cavitation nuclei, and the dissolved-gas concentration determines the initial radius and growth rates of those cavitation bubbles. The pressure p₀ within a bubble is equal to the sum of the partial pressures of the free gas p₉ and the vapor pressure of the liquid pᵥ at the working temperature: p₀ = p₉ + pᵥ. The following is the condition for static equilibrium in a spherical bubble:

\[ p = p₉ + pᵥ - (2κ/R), \]

where p is the external pressure in the liquid, κ the surface tension at the boundary of the bubble with the liquid, and R bubble radius.

We see from (1) that such a bubble begins to grow at a hydrostatic pressure in the liquid greater than that for a bubble filled with vapor alone [3].

There are three groups of factors influencing initiation and development of cavitation: contamination of the liquid, which gives rise to cavitation nuclei and determines the number of them; the physical properties of the liquid; and the flow hydrodynamic characteristics. In the present case, a reduction in viscosity (DF by comparison with oil) increases the maximum bubble size and increases their rates of growth and breakup, i.e., increases the danger of cavitation on pumping DF for identical conditions at the inlet, although it is easier to eliminate the cavitation by gradually disrupting the bubbles as they pass along the screws.

These three groups of factors interact to produce delays in the time of formation and growth of these cavities. That delay can be estimated as the ratio of it to the time of transit through the cavitation zone [3]. Initially, the bubbles may be small for vapor cavitation, but they attain the necessary size by diffusion. It has been pointed out [3] that the time required by an air bubble to grow by diffusion from the initial size R₀ to the critical size R₉ for vapor cavitation is T₉ = 0.03–0.1 sec. The screw length in a 3 V 63/25 pump is t = 180 mm, and the zone with the minimum pressure is at a distance l = (0.3–0.5)t = 54–90 mm (in accordance with the viscosity) [1, 4]. The flow speed necessary for bubbles not to attain the critical size is in the range from \( v_{\text{min}} = l/T₉ = 540 \text{ mm/sec} = 0.54 \text{ m/sec} \) to \( v_{\text{max}} = 3000 \text{ mm/sec} = 3 \text{ m/sec} \).

As DF has low viscosity, the bubble growth rate is high. With \( T₉ = 0.03 \text{ sec} \) and \( l = 54 \text{ mm} \), we get the necessary flow speed to prevent the bubbles from attaining the critical size as \( v \geq 1.8 \text{ m/sec} \). The time taken for a gas to dissolve is greater than


the time for its release from a liquid. Therefore, the necessary screw length to dissolve the gas, if it is necessary to eliminate cavitation, should be greater than the critical length $L_{cr}$, found from the condition for equality of the gas dissolution time to the critical time $T_{cr} = 0.03$–0.1 sec.

The length of the screws in a standard 3 V 63/25 pump is $L = 250$ mm, and the length over which the bubbles dissolve is $L_1 = L - 0.3t = 196$ mm; with lengthened screws, $L = 360$ mm, $L_1 = 306$ mm. The axial speed along the screws is $v_{ax} = 4.35$ m/sec, and then the critical distance is $L_{cr} = v_{ax}(0.03$–0.1 sec) = 130.5–135 mm. The gas dissolves quite rapidly (in 0.03 sec) in a low-viscosity liquid, so we can take $L_1 > L_{cr} = 130.5$ mm. That condition can be maintained, but the dissolution of the gas is affected by the pressure distribution along the screws. The gas dissolves favorably when there is a uniform pressure distribution along the screws, e.g., if there is partial leakage in the working parts because of the chamfer on the driving screw on the output side (in a 3 V 63/25 pump, the depth of the chamfer is 1 mm, height 8 mm).

The screws are quite well sealed in a standard pump, so the pressure increases only slightly from one closed chamber to another, and the main pressure difference occurs in the last chamber. Therefore, to eliminate cavitation, the screws should be lengthened. With short sealed screws, the pressure in the last closed chamber (if connected to the delivery chamber) increases sharply, and the cavities collapse instantaneously, which is accompanied by hydraulic shocks and deterioration in the vibration and noise characteristics. The pressure distribution is also influenced by the number of closed chambers, which is dependent on $L/t$.

Much experience in dealing with cavitation has been accumulated by the designers of spiral pumps, where cavitation often arises because of the high rotational speed. A standard example [5] operates without flow interruption by the onset of cavitation, i.e., when there are vapor-air bubbles. To eliminate the cavitation, the channels should be long enough. The larger $D/d$, the ratio of the outside diameter of the axial ring to the diameter of the sleeve, the greater the area of the blades, and the less the load, the better the anticavitation behavior.

Cavitation is very much dependent [6] on the liquid’s thermodynamic parameters. The evaporation rate (or extent of cavitation) is characterized by a thermodynamic criterion:

$$ B = \frac{V_v}{V_l} = \frac{\Delta T \rho_v c_f}{\rho_c r_v}, $$

in which $V_v$ is vapor bubble volume; $V_l$ the volume of liquid from which heat is drawn; $\rho_v$ the vapor density; $r_v$ the latent heat of evaporation; $\Delta T$ the temperature difference arising from the cooling of the liquid on evaporation; and $\rho_l$ and $c_l$ are respectively the density and specific heat of the liquid.

A ratio $B/B_{H_2O} = 3.1$ applies [6] for the cavitation criterion $B$ for kerosene (DF is close to kerosene) to that for water (water temperature +15°C). This means that the cavitation intensity (relative volume of vapor produced) for DF is 3.1 times larger than that for water and is even greater than that for oil. For most liquids, $B$ is less than for water.

When one calculates the lifting capacity of a spiral or axial pump, one uses the dependence of the initial cavitation coefficient $\lambda_{m}$ on the quantity $m$ [6], which is also called the flow parameter [7]:

$$ m = \frac{Q}{Q_0} = \frac{\tan \beta_\psi}{\tan \beta_l} = \frac{v_{it}}{v_{ax}}, $$

in which $Q$ is the flow rate; $Q_0$ is the flow rate at which the flow strikes the blades (teeth of the screw) without shock; $\tan \beta_\psi = v_{it}/v_{cv} = 2v_{it}/d_i\omega$; $\tan \beta_l = t/\pi d_i$; $v_{it}$ is the speed of the liquid in the inlet tube; $v_{ax} = to/2\pi$ is the axial velocity in the screws; $t$ the angular velocity of the driving screw; $v_{cv} = a d_i/2$ the circumferential speed of the screw; and $d_i$ is the screw diameter.

We see from (3) that the flow parameter is constant over the screw radius.

In experiments, the onset of cavitation is evaluated from the noise, with the vibration and noise characteristics indicating very clearly the approach to cavitation. If the vacuum-gauge lifting height exceeds about 0.2 m of water column (0.24 m from the limiting height at which the vibration and noise characteristics are normal), cavitation sets in.

Correspondingly, the vacuum-gauge suction height $H_u$ and the permissible cavitation margin $\Delta h_p$ [8] for normal vibration and noise characteristics are related to the permissible cavitation coefficient $\lambda_p$ which are given by

$$ \Delta h_p = \frac{v_{ax}^2}{2g} + \lambda_p w^2/(2g); $$

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