Efficiency model of pumping low viscosity fluids

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Abstract. This paper introduces the current research situation of pump efficiency, especially in pumping low viscosity fluids. Then we propose a simple and widely used efficiency model for the pump which just depends on the suction, discharge and leakage resistance coefficient. An experimental test rig is setup. After evaluating the efficiency of the pump in different conditions, it is found that the performance is quite different when pumping different medium. A phenomenon has been observed which results of the appearance of the BEP (best efficiency point), and our efficiency model can explain these testing phenomena very well.

1. Introduction
Pump efficiency is an interesting topic in many investigations [1-5]. The basic efficiency model of the pump can be found in numerous books. But there are many kinds of pumps and pumping medium in the world. There is no doubt that the leakage is different when pumping different medium by diverse pumps, which results in the difference of pump efficiency. So far, researchers have made many efforts about the model for the pump. Peng Xiwei et al. [6] modeled the efficiency characteristics of hydraulic pump based on neural networks. Yoshiharu Inagguma [7] presented a practical approach to leakage flow analyzing for various types of hydraulic gear pump, and obtained a calculating method of pump efficiency model indirectly. Bergada et al. [8] analyzed the leakage of axial piston pump and then deduced a series of equations of the leakage. In all, the above researches can be concluded in two parts which are establishing a specific efficiency equation of the pump and obtaining the efficiency equation indirectly under considering the leakage of the pump adequately. However, the first one is a local method which is weak in widely used in all kinds of the pump. And the second one is so complicated due to the difficult calculation process of the leakage.

Furthermore, the pumping medium discussed below have high viscosity, dozens or hundreds of times higher than petroleum fuel, which are not easy to leak out. The petroleum fuel sold at the service station generally includes gasoline, diesel and ethanol. As shown in table 1, gasoline has a low viscosity (about 0.5cSt at 20°C) and a high saturate-vapor pressure (more than 65kPa at 20°C).

Since the first fuel pump was invented and sold by Sylvanus F. Bowser in1885 [9], there have been few investigations focused on fuel pump efficiency. Though some investigations were conducted to the fuel pump efficiency, but they focus on the vapor pressure of gasoline and the vapor released during the automotive refueling systems [10-11]. The purpose of this investigation is to propose a simple and widely used efficiency model for the pump, and this model can be characterized the process of pumping low viscosity fluids.
Table 1. Properties of liquids at room temperature

| Medium | Density \((10^3 \text{kg/m}^3)\) | Viscosity \((\text{cSt})\) at 20°C | Vapor Pressure \((\text{kPa})\) at 20°C |
|--------|-------------------------------|--------------------------------|----------------------------------|
| water  | 1.000                         | 1.000                          | <4                              |
| gasoline | 0.738                        | <0.5                           | >65                             |
| diesel | 0.834                         | 3.0-8.0                        | <4                              |
| ethanol | 0.756                         | <0.6                           | <100                            |

2. An efficiency model for the pump

The overall pump efficiency is defined as the useful output power divided by the supplied input power. This definition may be mathematically expressed as:

\[
\eta = \frac{P_o Q_o}{T \omega}
\]

(1)

Where \(P_o\) is the discharge pressure of the pump, \(Q_o\) is the volume flow rate measured at the discharge port of the pump by flow-meter, \(T\) is the input torque on the pump shaft, and \(\omega\) is the angular velocity of the pump shaft. But according to Daniel Deneen’s research (shows in the figure 1), for low viscosity medium, the volume efficiency is the main part of the overall pumping efficiency due to the mechanical efficiency is much higher than the volume efficiency. So we only focus on the volume efficiency of the pump in this paper.

![Figure 1. Relationship between efficiency and viscosity](image)

For a vane pump, the volume efficiency is defined as:

\[
\eta_v = \frac{Q_o}{Q_i}
\]

(2)

Then we define a special parameter \(R\) as resistance coefficient in the pumping system, just like electric resistance in electrical engineering. At the suction port of the pump, the resistance coefficient \(R_i\) can be defined as:

\[
R_i = \frac{\Delta P_i}{Q_i}
\]

(3)

Similarly, the discharge resistance coefficient of the pump can be written as:

\[
R_o = \frac{\Delta P_o}{Q_o}
\]

(4)

And the leakage resistance coefficient of the pump can be expressed as:

\[
R_L = \frac{\Delta P - \Delta P_i}{Q_i - Q_o}
\]

(5)
Where $\Delta P_i$ is the differential pressure between suction pressure and atmospheric pressure, $\Delta P_o$ is the differential pressure between discharge pressure and atmospheric pressure, $Q_i$ is the suction flow rate of the pump.

From equation (2), (3), (4) and (5), we can deduce the volume efficiency equation:

$$\eta = \frac{R_L + R_o}{R_L + R_o} = \frac{1 + R_i / R_L}{1 + R_o / R_L}$$

In equation (6), the resistance coefficients are related to many factors of fluids, such as viscosity, temperature, flow rate, flow state, clearance of the pump and so on.

3. Experimental procedures and testing results

An efficiency testing rig for pumping low viscosity fluids is established including a vane pump and a flow-meter with the display system. A vacuum pressure gauge is installed at the suction port of the pump, with a measuring range of -0.9~0MPa. A pressure gauge is installed at the discharge port of the pump, with a measuring range of 0~2Mpa. Figure 2 shows the test rig.

![Test rig for a pumping system](image)

**Figure 2.** Test rig for a pumping system

Flow-rate changes with rotate speed, as shows in figure 3. And we can see that the flow-rate increases with the pump speed. However, the flow-rate remains above a certain level and it cannot be increased any longer even though the pump speed increasing. And this phenomenon is more obvious in low viscosity medium. The reason is that the leakage is also increased with the pump speed increases. The lower viscosity of the medium, the more the leakage is.

![Flow rate vs pump speed](image)

**Figure 3.** The relationship between flow-rate and pump speed
Figure 4 shows the relationship between volume efficiency and pump speed when pumping different medium. We can see that the volume efficiency of diesel is higher than that of gasoline. The volume efficiency raises at first, and then turns to decline as the rotate speed of the pump increases.

![Figure 4. The relationship between volume efficiency and pump speed](image)

4. Discussion

The phenomenon shows in figure 4 may be depends on fluid velocity. The volume efficiency of gasoline is lower than the diesel because the gasoline has a lower velocity which results in higher leakage. And this also leads to the volume efficiency declines as the rotate speed keeps increase. In this part, our motive is to explain this phenomenon with an efficiency model showed in part 2.

![Figure 5. The relationship between resistance coefficient and pump speed when pumping diesel](image)

Figure 5 shows the relationship between resistance coefficient and pump speed when pumping diesel. Compared with the resistance coefficient $R_o$ and $R_L$, $R_i$ seems to be very different as the pump speed increases. The values of $R_i$ keep up a constant one and very close to 0, which are much less than
$R_o$ and $R_L$. So without considering $R_i$ in equation (6) will not cause serious errors when analyzing the relationship between pump volume efficiency and resistance coefficient. Thus, equation (6) can be simplified as:

$$\eta_v = \frac{1}{1 + R_o / R_L} \quad (7)$$

To begin with, $R_o$ declines sharply while $R_L$ rises steadily as the pump speed increases, which results in the rise of volume efficiency $\eta_v$. Then $R_o$ keeps up rise but the rate of descent of $R_o$ turns to be slow, which results the slowly rising rate of $\eta_v$. Furthermore, $R_L$ turns to rise sharply and $R_o$ rise very slow, so the corresponding volume efficiency $\eta_v$ rises sharply. Finally, the sudden decline of $R_L$ and slow rise of $R_o$ lead to the sudden decline of $\eta_v$.

The discussion above shows that our efficiency model can explain the surface phenomenon of pumping low viscosity fluids. However, we do not know the underlying reason of this phenomenon exactly. And we think that this phenomenon may be caused by the transition of leakage flow from laminar flow to turbulence, but the supposition requires more works to be proved.

**Conclusions**

An volume efficiency model for fuel pump has been proposed in this paper. In this volume efficiency model, volume efficiency just depends on the suction resistance coefficient, discharge resistance coefficient and leakage resistance coefficient.

Efficiency of fuel pumping system is very dependent on the viscosity. For instance, gasoline has a very low viscosity, so the pumping system of gasoline has a low efficiency. As the pump speed increases, the volume efficiency curve rises in the first place, then turns to decline and keeps this trend. The underlying reason of this phenomenon requires more works to investigate.

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