Higher or Lower Density; Which One Governs

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Introduction

Pump hydraulic is probably one the most basic and simplest calculation that each process engineer should know. The purpose of this calculation is to specify pump main specifications such as flow rate, differential head, net positive suction head available ($NPSH_A$), pump maximum discharge pressure and hydraulic power. It is very simple for many people but when I was questioned last time about the effect of higher fluid density of pump operation and design specifications, I found myself in tough situation not being able to give complete straight forward answer.

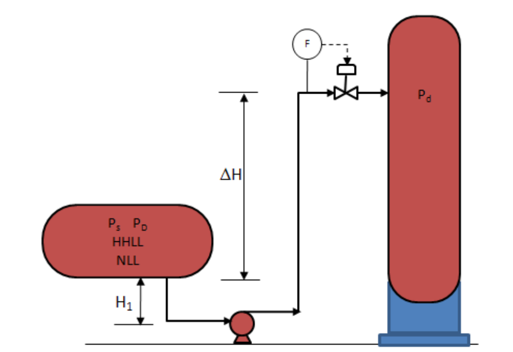

Figure 1 - Typical arrangment for controlled flow pump

This note assumes that pump rated flow has been fixed (at maximum possible volumetric flow among all possible operating cases) and reviews the pump hydraulic calculation relations to specify the effect of density on other pump's specifications.

Differential Head (DH)

Pump differential head, the difference between pump suction and discharge head, is calculated by following equation:

$$DH = \Delta H + \frac{\Delta P + \Delta P_{fe}}{\rho g} + \Delta h_{fp}$$

Where $\Delta P = P_d - P_s$ and ΔP_{fe} is the pressure drop of piping and instrumentation equipment with the fixed pressure drop. Refer to Figure-1 for more clarity. Pump has to deliver DH at design (rated) flow.

The first term in above equation is independent of fluid density but the second one increases as fluid density reduces. Third term is pipe (and fitting) frictional pressure drop which is calculated by:

$$\Delta h_{fp} = f \frac{l}{d} \frac{v^2}{2g}$$

Friction factor is function of Reynolds number as shown in Figure 2.

$$Re = \frac{\rho v d}{\mu}$$

Abbreviation	
d	Pipe internal diameter
e	Pump efficiency
f	Friction factor
g	Gravity acceleration
h	Head loss
H	Liquid head
l	Pipe length
v	Fluid velocity
Q	Volumetric flow
P	Pressure
ρ	Fluid density
Subscript	
D	Design
f	Frictional
p	Piping
e	Equipment
s	Suction
d	Discharge
v	Vapor

It is obvious that lower density will cause lower Re. According to Figure-2, lower Re is corresponding to higher friction factor and consequently higher frictional head loss (Δh_{fp}). Therefore third term also increases as density decreases. It should be noted that the effect of Re on friction factor is negligible in very high Reynolds (fully turbulent region).

In view of above, lower density will result in higher pump differential head.

NPSHA

The Hydraulic Institute defines NPSH as the total suction head in meter absolute, determined at the suction nozzle and corrected to datum, less the vapor pressure of the liquid in meter absolute. According to this definition:

$$NPSH_A = \frac{P_s - P_v}{\rho g} + H_s - h_{fs}$$

The first and last terms are density dependent as explained above. Lowering density results in increasing both terms which are acting in opposite directions. In view of this, there are two categories envisaged:

1) Operating pressure = vapor pressure (liquid at bubble point); for this kind systems, lower density is governing because:

   lower density ~ lower Re ~ higher f ~ higher h_{fs} ~ lower $NPSH_A$

2) Operating pressure > vapor pressure (sub-cooled liquid); since pump suction side head losses are usually minimized (ideally limited to 2-3 meters of liquid head), the first term should have the major effect on $NPSH_A$. Especially because few mbar is corresponding to couple of meters of liquid column. Although these kinds of systems should be reviewed on case by case basis but it can be generally concluded that the effect of density on pump suction head loss (h_{fs}) can be ignored and higher density is corresponding to lower $NPSH_A$.

Maximum Discharge Pressure (MDP)

Centrifugal pump casing and discharge system up to pump suction isolation valve is normally designed for pump maximum discharge pressure developed by pump in one of the following scenarios:

1) When pump discharge gets blocked; in this condition pump goes to zero flow and develops a head called shut-off head (SOH). Pump discharge pressure in this condition is:
   $MDP = P_s + \rho g\ (NLL \text{ or } HHLL + SOH)$
   SOH is in obtained from pump characteristic curve but in absence of vendor data, 1.2-1.25 times of DH is usually a good estimation.

2) When pump suction vessel reaches design pressure but pump delivers its normal differential head. Pump discharge pressure in this condition is:
   $MDP = P_D + \rho g\ (HHLL + DH)$

Pump design pressure is normally lager of item 1 or 2 except for cases in which pump discharge valve closure causes suction vessel to reach its design pressure such as column reflux pump. For such cases:

$$MDP = P_D + \rho g\ (HHLL + SOH)$$

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Regardless of scenario for which pump should be designed, it is quite clear that pump will develop higher discharge (design) pressure at higher density.

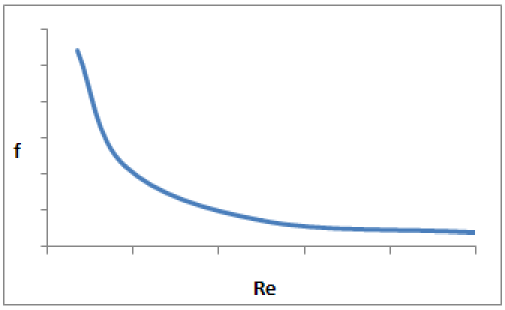

Figure 2 - Friction factor vs Reynolds No

Brake Horse Power (BHP)

Pump motor is selected base on required power as per below calculation:

$$BHP = \frac{\rho g\ DH\ Q}{e}$$

Pump will need more power when fluid density increases.

Conclusion

For controlled flow pump, operating point gets fixed by specifying volumetric flow rate and differential head. For this type of pump, differential head is constant as long as flow is maintained at designed flow. In other words, for installed pump head does not change due to density variations. Being fixed head machine, pump MDP and BHP will be higher when it handles fluid with higher density.

For pumps without flow control system, pump will adjust itself with actual system differential head. In this kind of systems, pump moves on its curve to reach flow rate at which delivered head is equal to actual system required differential head. Although method described above for controlled flow pumps can be also used for this type but to prevent designing the pump for unnecessary high MDP and BHP, it is recommended to calculate the pump differential head at highest and lowest possible densities and use differential head along with respective density in MDP and BHP calculations.

Pump MDP and BHP should larger of step 1 and 2:

1. Lower density and desired flow rate (Q_1) should be used for differential head calculation (DH_1). Since DH_1 is higher than step-2 differential head, then pump should be selected based on this differential head and SOH can be estimated based on that. Same differential head (DH_1) along with lower density (ρ_1) can be used to calculate MDP_1 and BHP_1.
2. Pump selected based on Q_1 and DH_1, will pump more flow when it handles higher density fluid. Pump flow rate at which below relation is satisfied can be calculated by iteration on flow and use of pump curve. Preliminary pump curve can be assumed as a straight line between (Q_1, DH_1) and (0, SOH).

$$\Delta H + \frac{\Delta P + \Delta P_{fe}}{\rho_2 g} + \Delta h_{fp} - DH_2 = 0$$

Where DH_2 is obtained from pump curve at Q_2 and Δh_{fp} is calculated at Q_2.

Calculated flow (Q_2), DH_2 and higher density (ρ_2) should be used for MDP_2 and BHP_2 calculation.

Contact

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