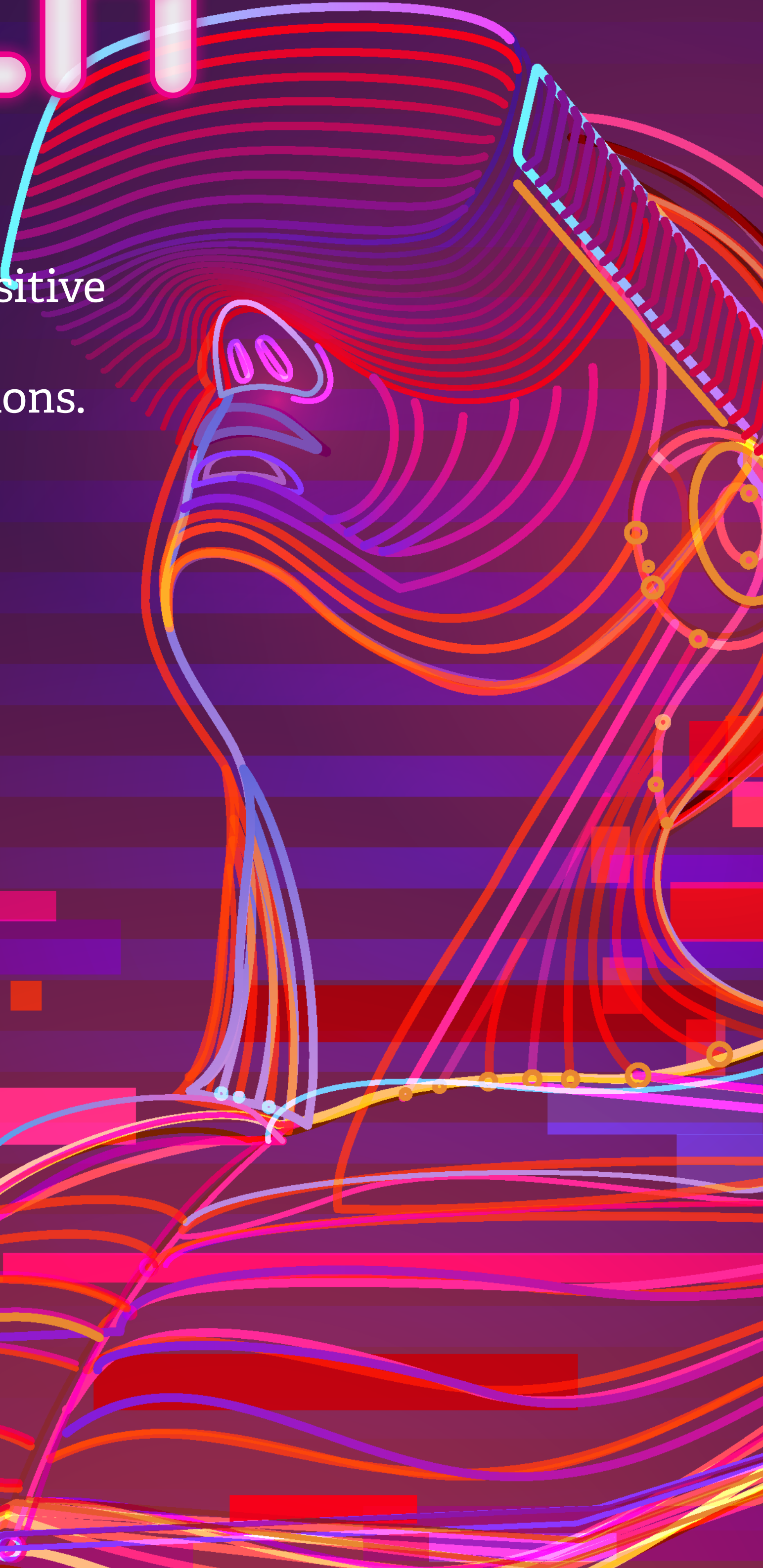
REALITY CHECK

Enver Karakas, Elliott Group, Cryodynamic Products, USA, discusses the realities of net positive suction head requirements on in-tank pumps in LNG applications.



Submerged electric motor pumps (SEMPs) are a well-established and highly reliable way to pump LNG. Retractable or in-tank SEMPs pump LNG in storage tanks, as well as in LNG carriers. This article addresses net positive suction head (NPSH) requirements, cavitation performance, and enhancement to NPSH for LNG in-tank pump applications. Technical terms, principles of cavitation, and determination of NPSH required (NPSHr) are also detailed, as well as utilisation of inducers commonly used in LNG in-tank pumps.

Importance of NPSH at LNG in-tank pumps

Cavitation behaviour of a centrifugal pump is an important performance characteristic due to the requirement of safe pump operation in the event of low suction pressure, or while emptying a storage tank or a container. In order to achieve acceptable NPSH performance and reduce NPSHr, pumps often utilise an inducer to delay cavitation and enhance suction performance. Inducer technology was initiated in the 1970s by NASA to improve the suction pressure of the rocket turbopumps.[1, 2, 3] Rocket turbopumps have very little inlet pressure to draw fluid into the pump internals, which are prone to cavitate. Today, inducer technology delays cavitation and enhances suction performance in industrial centrifugal pumps where suction performance is critical.

For in-tank pump applications, NPSHr determines the usable and non-usable liquid volume in an LNG storage tank. The height of the non-usable volume is mainly the liquid level that remains in the tank that cannot be processed or used due to the NPSHr limitations of the pump. Below this liquid height, the pump will suffer from direct and indirect impact of cavitation damage. Due to their construction, LNG storage tanks cannot handle internal pressure greater than 1 barg; tank builders often apply design parameters that enable the tank to withstand the static pressure due to liquid height. In these applications, an inducer increases the suction pressure to the pump in order to reduce the minimum required liquid level at the tank. A typical in-tank pump for an LNG application illustrates the minimum liquid level for clarification (see Figure 1). Since the footprint of LNG tanks can be as large as a football field, a small enhancement in minimum liquid height can result in considerable improvement in usable liquid volume.

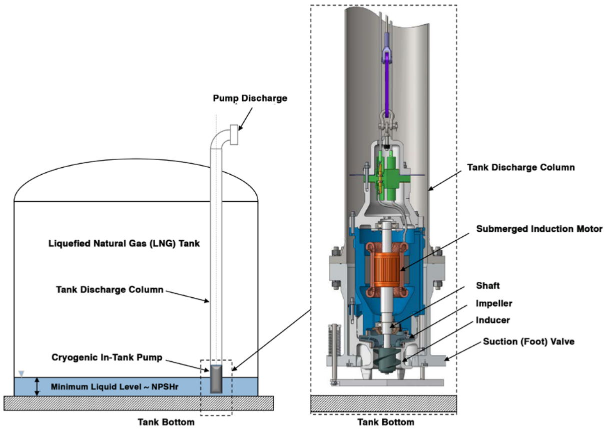


Figure 1. Typical LNG storage tank and illustration of minimum liquid height with a Cryodynamics® in-tank cryogenic pump.

When designing and building LNG storage tanks, the builder must specify the usable volume of the tank, and this value is used for guarantee purposes. The NPSHr of the pump determines the lowest usable liquid level and therefore directly relates to the usable tank volume. If the NPSHr level is higher, the builder must make the tank larger or taller to meet the usable volume specified, thereby increasing the size and cost of the tank. As a result, contractors continue to push for lower NPSHr in SEMPs. This has resulted in some unrealistic expectations and potential problems with reliability, as well as compromises in capabilities because of limitations in the design physics.

Definition of cavitation, suction specific speed and cavitation number

Cavitation is the formation of vapour bubbles in the low-pressure region within a flow. The formation of the vapour bubbles starts when the static pressure in the liquid reaches the vapour pressure (p_v) of the liquid for a given temperature. The cavitation inception, and the tendency to cavitate, is defined in a non-dimensionalised form as follows:[4]

$$\sigma = \frac{(p_1 - p_v)}{\frac{1}{2}\rho U^2}$$

where σ is the cavitation number, p1 is the suction pressure or the static pressure due to liquid height for in-tank pump applications, and U is the reference velocity. In the context of centrifugal pumps, three discrete cavitation numbers relate to the pump's cavitation characteristics.[4] The first is the cavitation inception number, σ_i, which corresponds to the initial formation of vapour bubbles within the pump. The second is the critical cavitation number, σ_C, at which the pump's first-stage differential pressure drops by 3% with a decrease in suction pressure. Further reduction in suction pressure results in a major differential pressure loss at the pump, corresponding with the breakdown cavitation number, σ_b. In industrial pump applications, the NPSHr of the pump equals the suction head that corresponds to the critical cavitation number. Often referred to as NPSH3, this implies that pump first-stage head loss is 3%. Figure 2 illustrates the important cavitation parameters for a given flow rate of a pump.

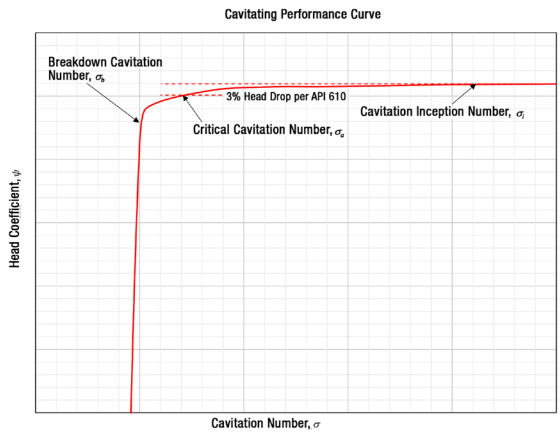


Figure 2. Performance of a centrifugal pump for a given flow point. Cavitation numbers are shown.

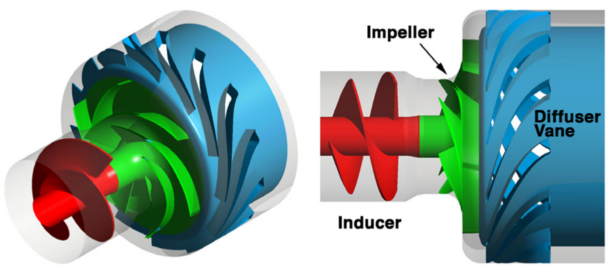


Figure 3. Components of Cryodynamics® pump hydraulics consist of an inducer, an impeller and the diffuser vane.

Based on the NPSH3 (or NPSHr), the best efficiency point (BEP) equals the flow rate that corresponds to the maximum efficiency attained (Q) and the rotational speed of the pump (N) – a dimensionless number that describes the characteristics of the suction (cavitation) performance of a pump based on the inducer and impeller design. This dimensionless number is the suction specific speed (Nss), which is calculated as follows:

$$Nss = \frac{N\sqrt{Q}}{NPSHr^{0.75}}$$

Nss has become the accepted parameter to evaluate the suction capability or cavitation performance of a pump with regards to NPSH3. With the reduction in NPSH3 for a given rotational speed and flow rate, the Nss will increase. The higher the Nss, the better the cavitation performance of a pump. Therefore, pump manufacturers often increase the Nss to meet and exceed the NPSH3 requirements outlined by the contractors.

Inducers aid in reducing NPSHr and advanced computer simulations of multiphase flow

An inducer is fundamentally an axial impeller with two to four long blades upstream of the impeller, which produces little inlet blockage. The inducer works with developed cavitation. It increases the pressure upstream of the actual impeller to the extent that the impeller operates without a cavitation induced head drop. An inducer typically allows a reduction in the value of the NPSHr of a pump to half of the NPSHr value without an inducer.[5] Figure 3 illustrates a typical helical constant pitch inducer by Cryodynamic Products, including the impeller and diffuser vane. Each inducer is designed by considering the impeller eye geometry to achieve maximum cavitation performance; that is, each inducer is custom designed with a matching impeller to meet application requirements.

Cryodynamic Products uses helical type constant and variable pitch inducers to achieve Nss ranging from 35 000 to 75 000 US units while maintaining high flow out capabilities. Computational fluid dynamics (CFD) simulations aid in the design and development of new inducers (Nss > 90 000 US units). With the advancements in computational capabilities, cavitation performance is predictable with the behaviour of the bubble dynamics and vapour formation within pump internal passages. Figure 4 illustrates a typical multi-phase CFD simulation result.

With the help of two-phase CFD simulations, the vapour formation and the flow characteristics of two-phase fluid, deficiencies within the inducer design, and impeller suction can be easily determined and addressed. Figure 5 illustrates cavitation performance in terms of NPSH3 of the actual test and the prediction by CFD simulations.

Compromises in NPSHr enhancement and pump operation under cavitation

Several problems occur when trying to reduce the NPSH to a point at which breakdown cavitation occurs. Firstly, the ability to predict this phenomenon both during factory tests in LNG, as well as in actual operation, is extremely difficult. When running a pump in a relatively small test tank in a closed loop LNG test stand, it is almost impossible to ignore the vapour pressure and its effect on NPSHr.

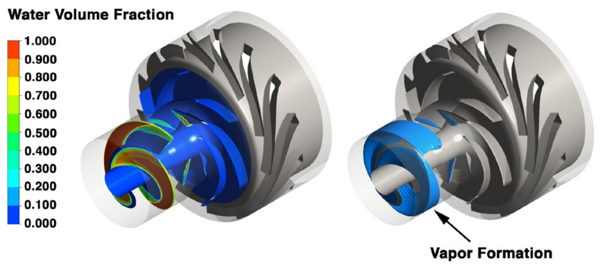


Figure 4. Vapour volume fraction and vapour formation (blue) at pump suction side.

Results obtained in testing can vary widely, depending on many variables, such as entrained nitrogen gas content or amount of non-condensable gases. Test results may be quite different from actual results obtained from an installed pump in a very large storage tank with little or no vapour pressure. It is common to obtain much more accurate NPSHr results in the large storage tank versus a closed loop test environment.

Another issue is the compromise between the pump's non-cavitating performance (flow versus head and efficiency) and the cavitation performance (NPSHr). Often, the implementation of aggressive inducers, such as the ones in turbo pump applications with aggressive head (pressure) increase, can result in poor non-cavitating performance. This is mainly due to the blockage caused by the aggressive inducer at the suction of the pump not allowing the pump to reach design maximum continuous flow rate.

The next problem is the mechanical effect that extreme cavitation may have on the pump. When NPSH < NPSH3, the collapse of large vapour pockets instigates higher vibration. Increased vibration causes deflection of the pump shaft at the inlet end, leading to wear ring rub, which over time is detrimental. In an LNG pump, due to the low viscosity of the liquid, the running clearances are smaller than on other pump types, and shaft deflection becomes even more important to prevent premature wear. The pump designer can improve the situation by increasing the shaft diameter to stiffen the shaft at the inlet end of the pump, but the forces involved are as unpredictable as the amount of cavitation itself, leaving a degree of uncertainty.

It is interesting to note that cavitation in LNG does not damage the material surfaces as water does. On an elementary level, this can be recognised by the fact that pumped LNG is primarily liquid methane, which is farther removed from its phase triple point than water, so the energy released in LNG vapour collapse is much less. This is explained by the physical differences between cavitation in water and other liquids, such as LNG, which are well-documented.[6]

In SEMPs, LNG provides pressure for axial thrust balancing, as well as cooling and lubricating the main ball bearings. In addition to radial vibration, as cavitation occurs, the possibility of vapour affecting the axial thrust balance of the hydraulic section, as well as the main bearings of the pump, also becomes an important consideration. With the very low viscosity of LNG, the fluid film build up on the ball bearings is extremely thin, and any upset in the thrust load can cause added heat or metal-to-metal contact, which may reduce pump reliability.

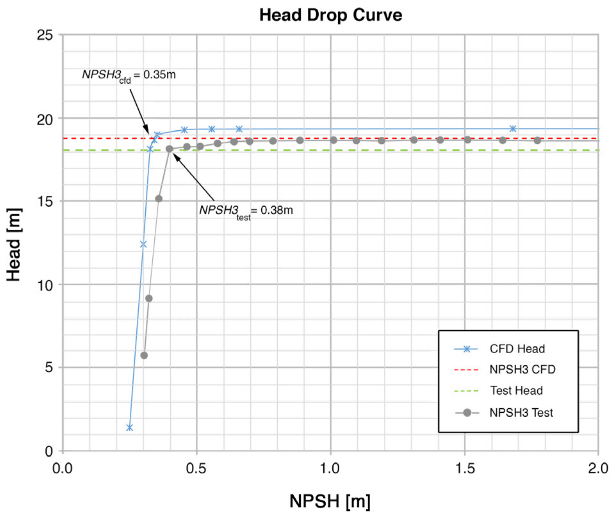


Figure 5. Cavitation performance – test results versus CFD predictions.

Conclusion

While newer design methods and tools have allowed pump designers to improve the NPSHr for in-tank pumps used in LNG applications, tank builders, plant operators, process engineers and equipment purchasers should be aware of the potential issues and compromises surrounding very low NPSHr requirements and their effects on reliability and non-cavitating performance. By recognising the realities of cavitation physics, design experience, and through close consultation with experienced LNG pump suppliers, an open and honest approach to process and tank design is the best recipe to successfully meet the desired goals of high reliability, as well as low NPSHr. **LNG**

References

1. JAKOBSEN, J. K., "Liquid rocket engine turbopump inducers", NASA Technical Report, SP-8052, (May 1971).
2. SCHEER, D. D., HUPPERT, M. C., VITERI, F., and FARQUHAR, J. "Liquid rocket engine axial-flow turbopumps", NASA Technical Report, SP-8125, (April 1978).
3. KOVICH, G., "Cavitation performance of 84 deg helical inducer in water and hydrogen", NASA Technical Report, TN-D-7016, (December 1970).
4. BRENNEN, C. E., "Hydrodynamics of Pumps", Concepts ETI, Inc, Norwich Vermont, USA, Oxford University Press, Oxford OX3 6DP, England, (1994).
5. GULICH, J. F., "Centrifugal Pumps", ISBN 978-3-642-40114-5.
6. STEPANOFF, A. J., "Cavitation in Centrifugal Pumps with Liquids other than Water", ASME Journal of Engineering for Power, (January 1961), pp. 79 – 90.