Cavitation in Centrifugal and Axial-Flow Pumps

Cavitation is well recognized as a phenomenon that may seriously affect performance or life of centrifugal and axial-flow pumps. It is therefore important to understand what cavitation is, when it will occur, what it potentially can cause, and how it can be controlled to avoid serious pump malfunctioning due to improper inlet conditions.

By Frank Visser, Principal Engineer, Flowserve

Cavitation[1]

Cavitation is defined as the process of formation and disappearance of the vapor phase of a liquid when it is subjected to reduced and subsequently increased pressures at constant ambient temperatures. The formation of cavities is a process analogous to boiling in a liquid, although it is the result of pressure reduction rather than heat addition. Nonetheless, the basic physical and thermodynamic processes are the same in both cases. The entire process of cavitation is governed by fluid inertia (fluid dynamics) and heat and mass transfer (thermodynamics).

Clearly, from an engineering and design perspective there are two basic questions regarding cavitation. First, one has to answer the question whether cavitation will occur or not, and second, if cavitation is unavoidable, the question is whether a given design can still function properly. Economic or other operational considerations often necessitate operation with some cavitation, and under these circumstances it is particularly important to understand the (deleterious) effects of cavitation.

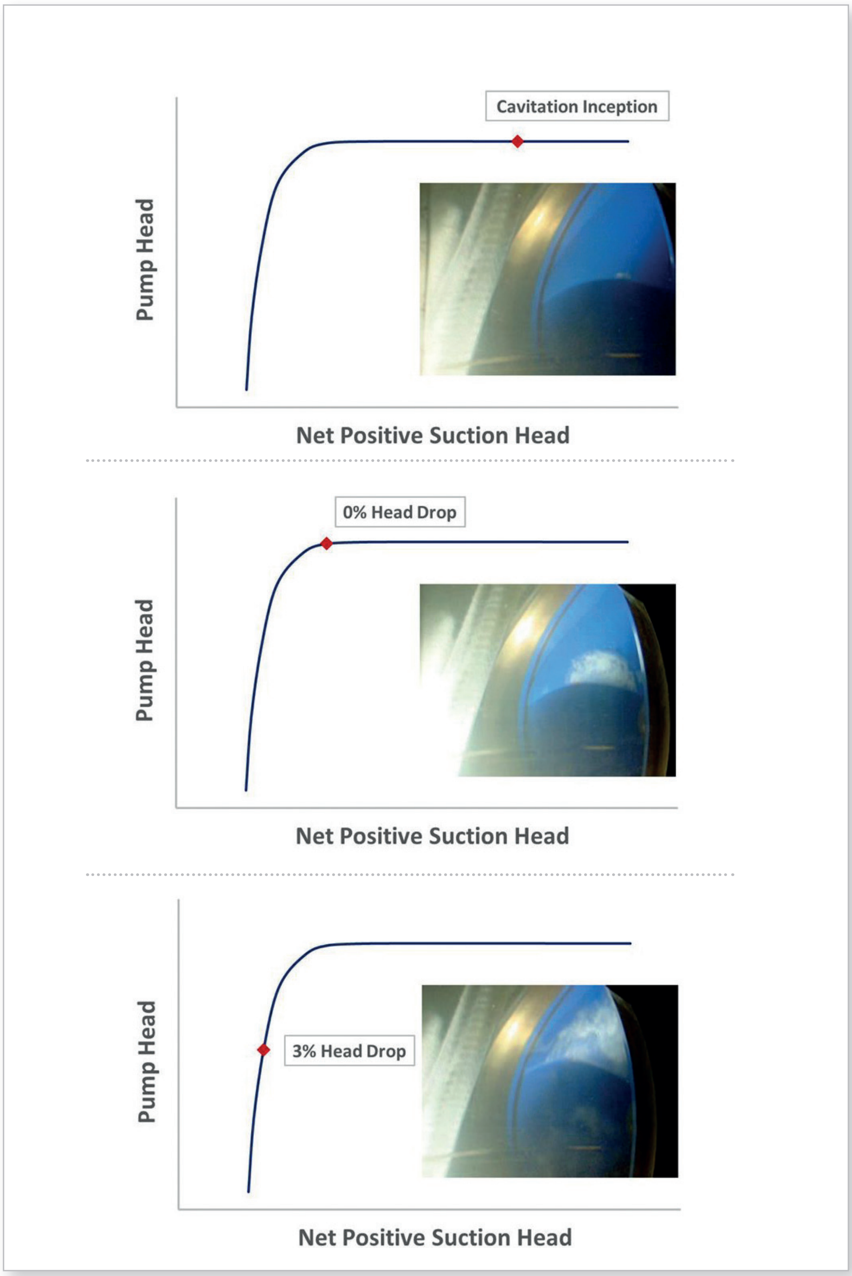

Figure 1: Head Drop Curve.

[1]First use of the word cavitation is credited to Robert Edmund Froude (1895).

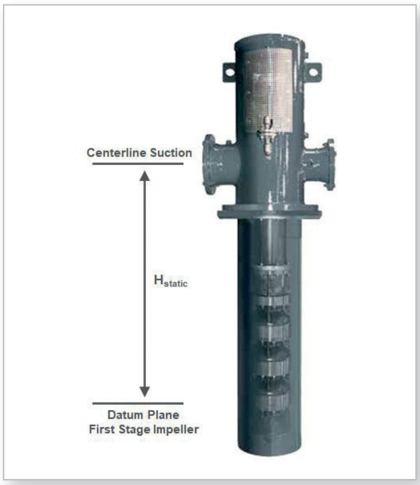

Figure 2: NPSH Datum Plane.

Net Positive Suction Head

The potential for cavitation when dealing with pumps is typically evaluated by a parameter called Net Positive Suction Head (NPSH). This is defined as the total head of the fluid at pump suction ($H_{S,T}$) above the vapor pressure of the fluid (in terms of head, H_V): NPSH = $H_{S,T}$ - H_V. It can be seen as a measure expressing the margin against vaporization of the fluid entering the pump.

Using a parameter like NPSH one can define various critical values corresponding to certain stages of cavitation or cavitation phenomena. Typically, this includes – but is not limited to – cavitation inception, head drop inception, percentage head drop, and performance breakdown.

Cavitation Inception and Three-Percent Head Drop

The first appearance of cavitation when gradually lowering pump suction pressure from a level high enough to suppress cavitation is called cavitation inception. When pump suction pressure – or NPSH – is decreased further from this inception level, the region of cavitation enlarges, eventually starting to cause fluid-born noise (audible and/or non-audible), performance change (head loss), and finally full head breakdown.

By the time the inlet pressure is lowered enough to cause a certain percentage drop in pump head, cavitation is always fully established. Before reaching that stage there is already a significant amount of cavitation without the pump head being affected by it. This is illustrated by Figure 1, which shows so-called head drop curves. In a curve like this pump head is plotted against NPSH for constant flow rate (Q) and constant speed (N). For multistage pumps one would plot the head of the suction stage.

NPSH Required

NPSH required (NPSHR) constitutes the condition of having a specific amount of cavitation being developed inside the pump, or a specific cavitation criterion being established. This implies that a statement on NPSHR is meaningless without specifying the associated condition. NPSHR for a particular condition is a function of volumetric flow rate and speed of the pump.

Historically, the condition of three percent head drop is taken as the NPSHR for (rotodynamic) pumps. Unfortunately, this has led to a lot of misconception since many interpret NPSHR as the one needed to run free from cavitation, while in reality it constitutes the NPSH needed to have the pump cavitating to such an extent that it loses three percent of its head. Current practice of using NPSH3 remedies this misconception.

Other typical and popular NPSHR criteria include: NPSHi for cavitation inception, NPSH0 for the starting of head drop and NPSH1 for one precent head drop. NPSH0 is sometimes termed “incipient NPSH”, which should not be confused with NPSHi.

NPSH Datum Plane

NPSH should always be reference against a datum plane (elevation). Typical NPSH datum planes include: i) horizontal plane thru impeller (shaft) centerline; ii) top of foundation; iii) impeller eye for vertical pumps or horizontal plane thru suction flange centerline for vertical can pumps. When changing from one NPSH datum plane to another the NPSH needs to be corrected for the static height and any head loss between the two datum planes (Figure 2).

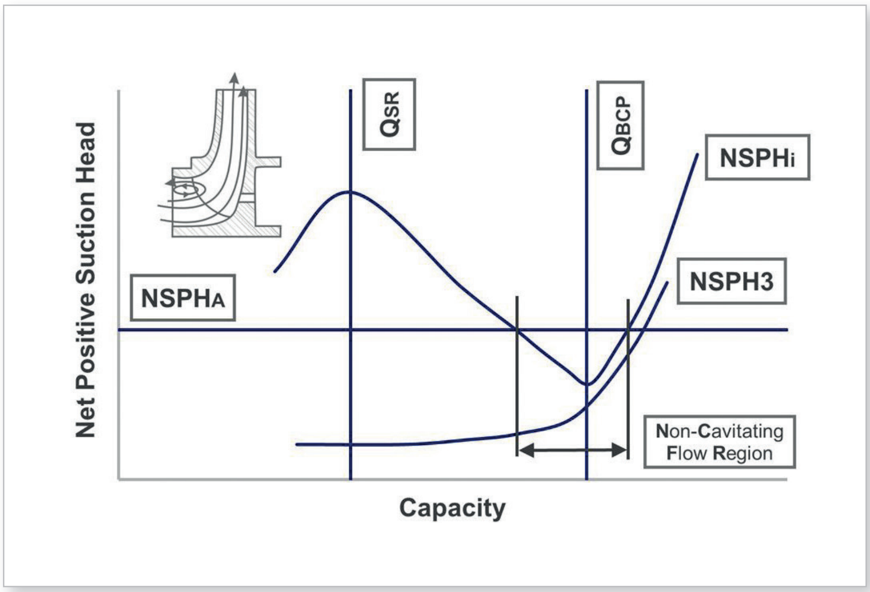

Figure 3: NPSH Characteristics.

Figure 4: Cavitation damage.

NPSH Characteristics

Figure 3 shows typical NPSH characteristics that can be identified for centrifugal and axial-flow pumps. In this figure NPSHA is the NPSH available as provided by the system. Beyond the so-called shockless-entry capacity—or best cavitation point (BCP)—the NPSH3 is seen to follow the steep rise of the inception curve (NPSHi). Below QBCP the inception curve shows an absolutely striking departure from the shape of the conventional NPSH3 curve. Instead of decreasing with decreasing capacity, it rises until a local maximum is reached. This local maximum is of particular importance since it identifies the onset of suction recirculation. It can further be seen that a cavitation free region of operation will exist for those capacities where NPSHA > NPSHi. Outside this region the pump will cavitate and the extent of cavitation will depend on the operating capacity of the pump.

Cavitation Damage

Figure 4 shows an example of an impeller with cavitation damage. Cavitation damage starts somewhere beyond inception and will disappear near head break-off, with maximum erosion rate occurring somewhere in between, and often marginally before NPSH3 (Figure 5). A more accurate description is difficult to give since many parameters influence bubble geometry and its potential for causing damage. For instance, impeller material, air content, NPSH available, vane geometry, inlet geometry, type of cavity, fluid density, and fluid temperature, to name a few, can be contributors or inhibitors of cavitation damage. Furthermore, with maximum erosion rate occurring marginally before NPSH3 one need to be cautious about specifying the NPSH margin (i.e., NPSHA-NPSH3). Without given it proper thought, the NPSH margins suggested in literature may result in running the pump exactly near maximum erosion rate, if cavitation erosion actually occurs.

In order to have cavitation erosion the cavitation vapor pockets need to implode on or near a material surface, and the energy release must exceed the cavitation resistance of the surface material. Since the latter is hard to quantify many experimental and semi-empirical studies have attempted to correlate between cavity shape and damage potential, and research in this field is still ongoing. The only certainty is that the absence of visible cavities means that cavitation damage will not be an issue. This fact is used in some conservative designs, such as liquid sodium pumps, and some water injection applications, where the NPSH available is high enough to suppress cavitation. The occurrence of cavitation erosion is also less of a worry when pumping hydrocarbon mixtures due to the absence of a vapor pressure. The vapor-liquid region of such mixtures, enclosed by the bubble and dew pressure, prevents any violent (high energy) cavity implosions.

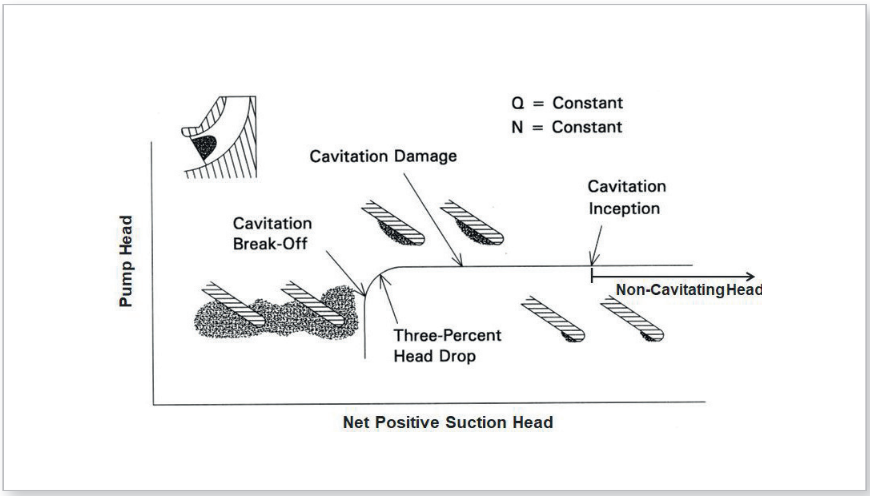

Figure 5: Cavitation Phenomena.

Suction Specific Speed

Suction specific speed (S or NSS) is often seen as the key indicator determining the susceptibility to cavitation. This, however, causes a lot of misunderstanding and misinterpretation of the concept of suction specific speed. To understand this, one most realize that it is a quantity that originates from scaling model pumps and prototypes, and that is has a clear definition: suction specific speed is the running speed (RPM) of a geometrically identical impeller/pump scaled at a (suction) specific diameter, such that it will have an NPSH of 1 m [1 ft] at a flow rate of 1 m^3/h [1 USGPM]; as such (by similarity) the well-known equation to calculate suction specific speed is readily found: $NSS = N\,Q^{1/2} / NPSH^{3/4}$.

Depending on the set of units used this will produce a particular number. Factoring in the acceleration due to gravity (g) and using a consistent set of units yields the universal (dimensionless) number: $S = N\,Q^{1/2} / gNPSH^{3/4}$.

Suction specific speed is a relative index number that should be used and judged with extreme caution. In order to have some consistency the widespread rule is that it should be evaluated at pump peak efficiency capacity, with maximum diameter impeller fitted in the pump. Although this leads to a workable definition in practice, it has some serious drawbacks: i) The volute or diffuser characteristic will greatly determine the peak efficiency capacity of the pump, and ii) for multistage pumps the series stages may have a peak efficiency capacity quite different from the first stage. This makes S or NSS very sensitive to the construction of the entire pump whereas it should only reflect the suction capabilities. A way to overcome this objection is to evaluate S or NSS at the so-called shockless entry capacity of the (suction) impeller.

Lastly, it is paramount to understand that suction specific speed is not an indicator to warrant healthy pump selection or operation in relation to NPSH. Unlike common belief it is not a limiter. At best it can be a caution sign if it is outside the ballpark.

About the Author

Frank Visser is Principal Engineer at Flowserve, Global Engineering Services, in Etten-Leur, The Netherlands. He joined Flowserve in 1995 and has held several positions in research, development, and (product) engineering. His key expertise and interests relate to fluid mechanics, CFD and thermodynamics of (centrifugal) pumps and hydraulic turbines. He has authored & co-authored multiple technical papers in journals and proceedings, and lectured at various symposia. He has a BS and MS in Mechanical Engineering, and a PhD in Technical Sciences. He has received the ASME 2017 Sankaraiyer Gopalakrishnan-Flowserve Pump Technology Award, is a member of the Industrial Advisory Board for the J.M. Burgers-centrum (JMBC), National Research School for Fluid Mechanics in the Netherlands, and a former Associate Editor for ASME Journal of Fluids Engineering.