The importance of optimising sump design for the reliable operation of rotodynamic pumps

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Why is it important to ensure resilience in a pumping station?

A pumping station is:

- Expensive to build
- Expensive to run, and
- Even more expensive when it stops running.

This paper explores how intake conditions affect all of the above and could make or break a typical project in the water and wastewater industry.

So what are the needs of the pump?

Liquid should be presented to the pump at the point of entry in a smooth and uniform way and at an adequate pressure. In order to achieve this we need to avoid the following conditions: air entrainment; pump pre-swirl; uneven velocity profile at the pump impeller; surface and submerged vortices; solids settlement; unstable flows and hydraulic impact on other mechanicals in the sump.

So how do we ensure the pump operates correctly, achieves its process guarantees and delivers cost effective water and wastewater services to the end user?

It's important to ensure that you procure robust and reliable equipment. Equally, the infrastructure must be optimised and validated to provide ideal inlet conditions. The best way to do this is to independently validate the design.

Identifying any detrimental intake conditions as early as possible in the design process is critically important. The best solution is the modelling process, which allows not only the identification of problems but also the development of solutions before construction begins.

PHYSICAL MODELLING

Physical modelling entails the construction and testing of a scale model by passing a liquid flow through the model in order to understand the hydraulic conditions in the final structure. The size of the model will be determined by the scale factor and

Typical submersible pump installation

the model extent, which must be selected to ensure representative boundary conditions for the model. BHR typically includes the entire pump sump along with any other structures close enough to affect flow conditions entering the sump. The level of detail in the model must be gauged using engineering judgement and knowledge; failing to include crucial detail could invalidate the model, but including too much detail can compromise timescales and budgets.

GETTING THE SCALING RIGHT

A correctly scaled model will allow you to thoroughly validate your design.

Obviously the smaller the model is, the cheaper its cost. However it's important to balance the cost of modelling with the accuracy you can expect from the scale. Scaling is accomplished by maintaining similar Froude number, a dimensionless number which is the ratio between inertial and gravitational forces. This leads to some unintuitive scale factors for flowrate and velocity which must be understood in order to achieve similarity between the model and the full size structure. In a 'Froude scale' model, other dimensionless numbers will of necessity be different to the full scale; these must be checked to ensure that the level of verisimilitude between the model and the real structure is understood. Reynolds number, for instance, is the ratio of inertial to viscous forces, defining whether flow conditions are fast and turbulent or smooth and laminar, while Weber number concerns the significance of surface tension effects and so effects surface turbulence and vortex formation.

COMPUTATIONAL MODELLING

Computational fluid dynamics (CFD) entails the creation of a digital 'mesh' representing the geometry of the structure to be modelled. This mesh comprises the entire volume of the fluid to be modelled; the internal volume of the pump sump and associated flow regions.
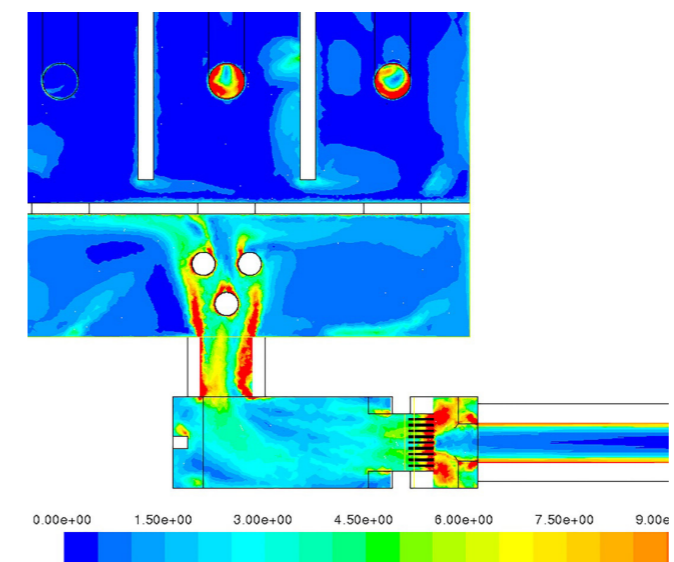
Velocity map of typical pump sump

The above described decisions regarding the extent of the model and level of detail required apply equally to CFD as they do to physical modelling.

Additionally, the size of the mesh, or number of cells per unit volume, must also be decided upon, and possibly altered to provide more detail around key locations. The equations of hydraulics are then used to incrementally 'step' the model through time, predicting the hydraulic behaviour of the structure.

In general, CFD has lower costs associated with initial model construction and major changes to the geometry, but higher costs for minor modifications and incremental development work than a physical model. This makes CFD particularly suited to an earlier role in the design process. CFD also allows for simpler extraction of data from the model, making it possible to produce a wide variety of graphical outputs quite rapidly.

NPSH - THE FIRST CRITERIA FOR CONSIDERATION

The first criteria for any pump intake is to ensure adequate absolute suction pressure at the impeller inlet (NPSH) to allow the pump to operate. The available NPSH for continuous operation must exceed that at 3% head drop by an adequate safety margin in order to avoid a loss of performance, noise, and vibrations, or even cavitation erosion.

Pump manufacturers generally provide NPSH'R' data in the form of a 3% head drop NPSH curve.

Detailed in ISO & ANSI standards, this is a measured point at a corresponding flow rate when the developed head of the pump drops by 3%. NPSH'R' varies with flow and on high specific speed pumps can pronouncedly vary as flow reduces from that of "Best Efficiency Flow" as a result of recirculation to suction as well as at increased flow beyond "Best Efficiency Flow". The pump is therefore already cavitating at this 3% head drop point and suffering from reduced output, as a result of a percentage of the volumetric capacity of the pumps impeller being taken up by vapour, rather than liquid.

The NPSH margin should not be considered as a constant and is defined often as a ratio: NPSH'A'/ NPSH'R'. The required safety margin/ratio tends as a rule to increase with rising peripheral speed at the impeller inlet. Thus, pumps of varying hydraulic design need lesser or greater margins of NPSH. Withstanding any civil implications we would always suggest that increasing the margin of NPSH would be considered a good thing. To be completely cavitation free ratios of up to 5 or more may actually be required for some high suction energy applications.

We have stated that the available NPSH must exceed that at 3% head drop value by an adequate safety margin in order to avoid a loss of performance, noise, and vibrations, or even cavitation erosion.

CAVITATION

Cavitation results when the absolute pressure of the liquid at the pump impeller inlet approaches the vapor pressure of the liquid, causing vapor pockets to form and collapse (implode) as they pass through the pump impeller. The collapsing of the vapor bubbles creates noise and can be very destructive.

When present, cavitation often sounds as if "marbles" or "gravel" are passing through the pump. Cavitation at its inception however may not be so easily recognised as may not be audible to the human ear. As cavitation typically generates random, higher frequency broadband energy, which is sometimes superimposed with blade pass frequency harmonics (multiples), it can however often be detected by monitoring and analysing vibration.

WHAT ARE THE IMPACTS OF CAVITATION?

The primary concern is one of metal loss, which can occur even with a margin of NPSH above that of NPSH'R' and with no audible cavitation present. This metal loss tends to increase as the extent of cavitation increases.

Severe (through wall) cavitation damage to metallic components

As vibration increases it also starts to seriously impact on the mechanical integrity of the machine by damaging bearings and mechanical seals which if not addressed can quickly progress to the level of a catastrophic failure of the machine.

### SUMP DESIGN OPTIMISATION AND METHOD OF ANALYSIS

In order to understand whether or not pump intake conditions are detrimental and require modifications to the design, we must be able to both observe and quantify those conditions in the model. This is undertaken using a suite of observational tools.

UNDERSTANDING SWIRL

Pump pre-swirl is a rotation of the flow approaching the pump impeller and can be measured using a freely rotating 'vortometer' similar to an impeller with a blade angle of 0o to the incoming flow.

Swirl is affected by approach conditions to the pump, including everything from angle of approach to velocity. Any flow bias created by upstream conditions has the potential to lead to high pump pre-swirl.

If pump encounters pre-swirl in the same direction of rotation as that of the pump impeller, there is a tendency for the pumped head, pump input power and efficiency to decrease for a given output in terms of flow rate.
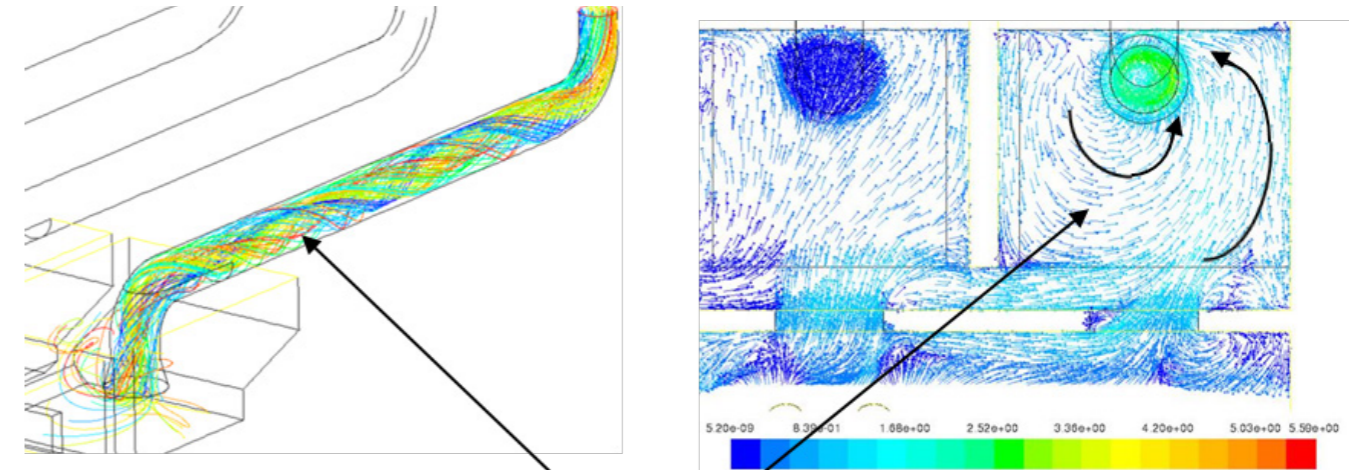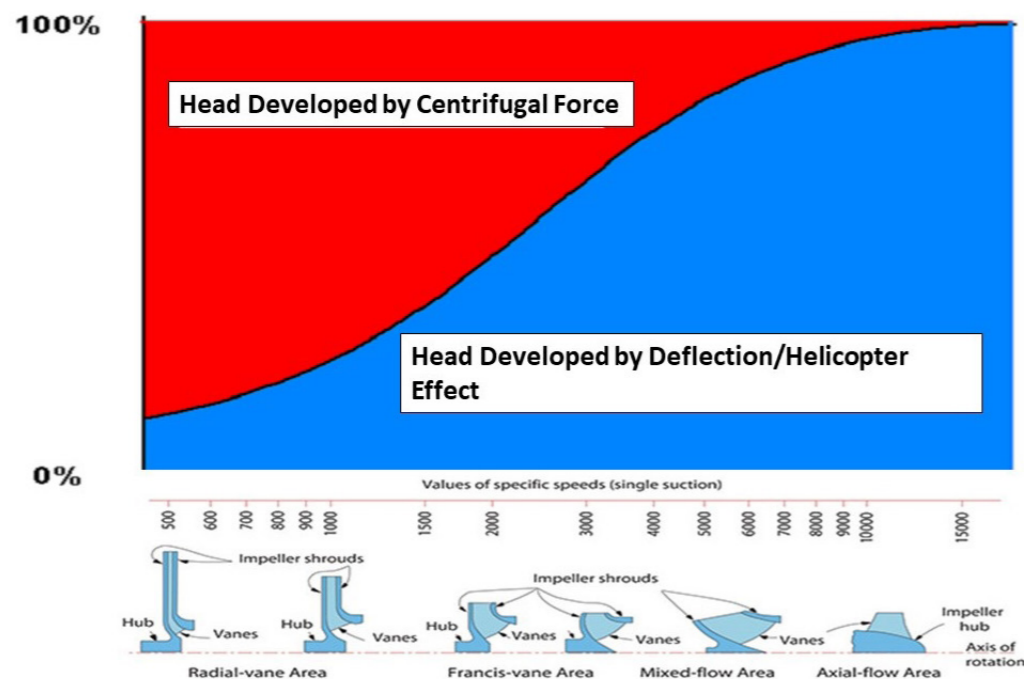

Bulk rotation in the pump sump and resultant pre-swirl in the pump suction pipe

Alternatively, if a pump encounters pre-swirl in the opposite direction to the pump impeller rotation, the generated head of the pump tends to increase at a given flow rate. It should be noted that the pump efficiency will drop more significantly than in the case of pre-swirl in the same direction of rotation. This can result in a significant increase in absorbed shaft power, which can create driver overload. To give some perspective on this, it would not be unusual for an axial flow pump to drop 30% in efficiency under such operating conditions.

In either case the pump will therefore not deliver as per its design output with varying potential impacts which can range from reduced efficiency to catastrophic failure.

As previously stated, to ensure efficient, problem free operation of any rotodynamic pump, approach flows to the pump inlet should be uniform and free of disturbances. Hence before we consider the likely impacts of various conditions encountered in less than perfect sump designs, it should be stated that pumps of different classifications are more or less susceptible to performance degradation when exposed to the same intake conditions.

Pumps of higher specific speed should be considered more susceptible to disturbances in the approach flow than those with lower specific speeds. Therefore to ensure efficient, problem free operation of any rotodynamic pump, approach flow to the pump inlet must be uniform and disturbance-free.Low specific speed pumps (radial flow pumps): Energy transferred from the impeller vanes to the pumped liquid in a low specific speed pumps is based on centrifugal force or the bucket effect, which can be considered a strong mechanism of energy transfer.

Source of developed head in rotodynamic pumps

HIGH SPECIFIC SPEED PUMPS (AXIAL FLOW PUMPS):
The mechanism to transfer energy is more a result of flow deflection (helicopter effect) which is a much weaker mechanism to transfer energy than centrifugal force.

MEDIUM SPECIFIC SPEED PUMPS (MIXED FLOW PUMPS):
Such pumps employ both mechanisms, with the effect of the stronger centrifugal force being gradually replaced with the weaker element of helicopter effect as specific speed increases to that of an axial flow pump.

VELOCITY DISTRIBUTION ANALYSIS

Velocity distribution at the plane of the pump impeller can be measured by several means, but BHR typically uses an array of Pitot-static tubes called a 'Pitot rake'. Velocity distribution is affected by similar conditions to pump pre-swirl with the addition of the form of the pump entry, as flow separation close to

the pump impeller can cause a significant problem.

Needless to say, when designing a pump, the designer will consider a uniform velocity distribution of flow entering the impeller inlet, hence the more the distortion to the uniformity of the velocity distribution pattern, the less likely it is that the pump will deliver the required output. As the individual vanes of the impeller are exposed to an uneven approach flow, they will be subject to alternating low and high flow conditions in the region of the velocity distortion. If such non-uniform velocity distribution is encountered with a none rotationally symmetric pattern, the likely outcome is that mechanical vibrations resultant of effectively hydraulic imbalance within the impeller.

AIR ENTRAINMENT ASSESSMENT

Air entrainment is observed visually, but awareness must be maintained of the effects of scale on entrained air. Due to a shift in the Weber number as the scale gets smaller, air entrainment will tend to be more severe in the full size structure than observations at model scale may suggest.
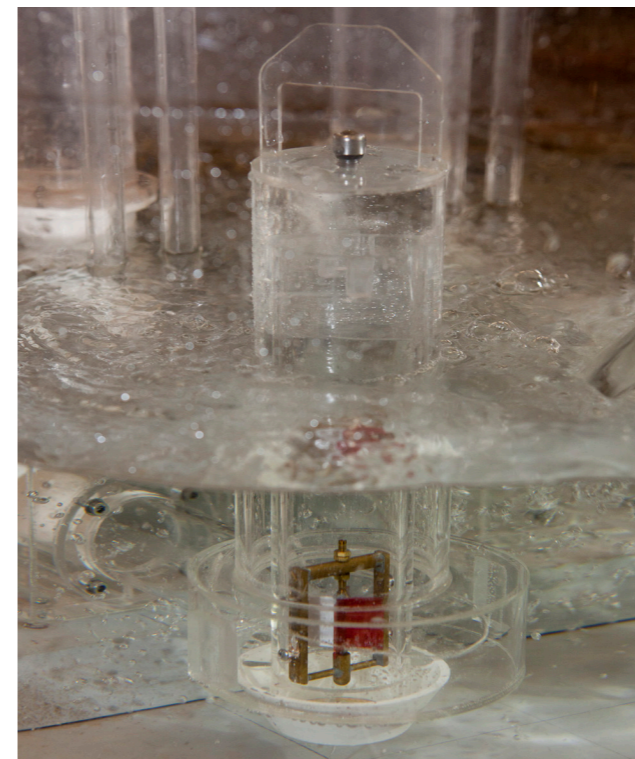
Even small percentages of air entering a rotodynamic pump can have a marked impact on pump performance and output. The margin of NPSH has a significant impact on a given volume of air entering a pump as the lower the absolute pressure at the impeller inlet the more a given quantity of air will expand.


Entrained air in physical model

A given quantity of air entering a pump at will expand proportionally to the ratio of the pressure change, as defined by Boyle's Law.

A well-formed surface or even subsurface vortices will ingest a significant amount of air and in order to put some perspective on this, one could consider $0.1m3$ of air entering a pump intake from a sump open to atmospheric pressure. Roughly 10m water gauge. If the margin of NPSH was 1.0m, the air volume would expand to near $1.0m3$. A tenfold expansion. Such a volume of air would cause air binding and substantially impact on the output and smooth running of any rotodynamic pump.

VORTEX TRACING

Vortices, both surface and sub-surface, are observed visually in physical models, sometimes with the aid of a visible tracer. Vortices close to the pump suction can lead to air entrainment as previously intimated. They can also cause a high degree of pre-swirl due to additional rotation and a significant imbalance of load on the impeller caused by the low pressure at the core of the vortex; this can lead to vibration and pump damage.
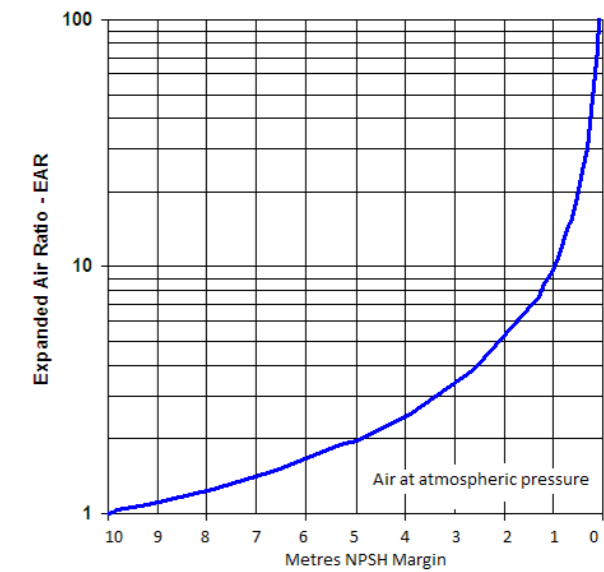
Air expansion versus NPSH

As well as the direct intake conditions discussed above, additional thought must be given to ensuring that any other parameters of interest or concern will be measurable. In order to ensure NPSH requirement is met, liquid depths must be on an appropriate order of magnitude for measurement. Flowrates and velocities must be in a range that can be accurately delivered and measured. Finally, we consider whether the pump bay width will allow access for observations and measurements to be made and for modifications to be installed?

DELIVERED BENEFITS

Advance modelling of new pump sumps, and changes to existing pump sumps, prior to construction work reduces risk. By examining hydraulic conditions before construction begins the possibility of unexpected hydraulic phenomena causing a failure to achieve required system performance is significantly reduced.

The longevity and maintenance performance of pumps and other systems can also be improved, since the effect of hydraulic conditions on the mechanical components can be understood and allowed for.

Early involvement of modellers can lead to a more elegant final solution. A simpler geometry might allow for improved access to the sump, fewer features to construct, and a reduced construction cost with substantial long term operational efficiencies.

COLLABORATION IS KEY

With both CFD and physical modelling there are significant benefits to be obtained through early collaboration between the designer and the modeller. A design review in the early stages can often avoid problems with the overall geometry, leading to a more elegant and cost-effective solution.

Ongoing engagement is similarly important, with good communication allowing the model(s) to remain relevant and productive as issues arise and are resolved. Subject to our client's requirements, BHR employs both CFD and physical modelling throughout the consultancy process, allowing close collaboration between the two that can produce the best possible outcome.

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