SULZER

Praktikerkonferenz Graz

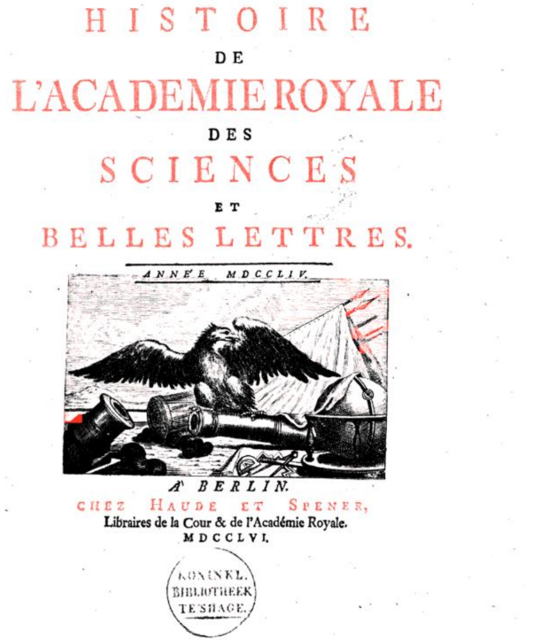
Cavitation in centrifugal pumps: physics, analysis, consequences, mitigations.

Bruno Maroccia, Stefan Berten

Introduction

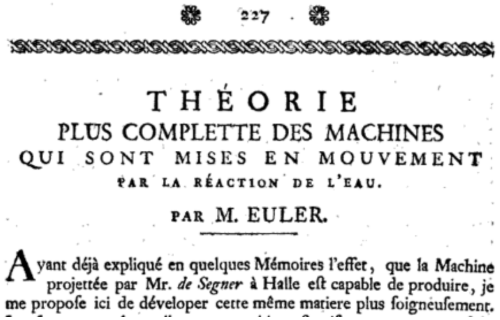
- Cavitation as physical phenomenon is known since many years:
  - Euler, 1754: « A more complete theory of machines that are set in motion by reaction with water », Mémoires de l'Académie Royale des Sciences et des Belles Lettres à Berlin, vol. 10 (1754), pp. 227-295 (via Google Books).

- It is still nowadays one of the most investigated phenomena in hydraulic machinery because:
  - Operation limits, operating conditions and consequently the physical size of the machines are determined by cavitation limitations



HISTOIRE
DE
L'ACADEMIE ROYALE
DES
SCIENCES
ET
BELLES LETTRES.
ANNÉE MDCCLIV.

A BERLIN.
CHEZ HAUDE ET SPENER,
Libraires de la Cour & de l'Académie Royale.
MDCCLVI.



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THÉORIE
PLUS COMPLETTE DES MACHINES
QUI SONT MISES EN MOUVEMENT
PAR LA RÉACTION DE L'EAU.
PAR M. EULER.

Ayant déjà expliqué en quelques Mémoires l'effet, que la Machine projettée par Mr. *de Segner* à Halle eft capable de produire, je me propofe ici de développer cette même matiere plus foigneufement.

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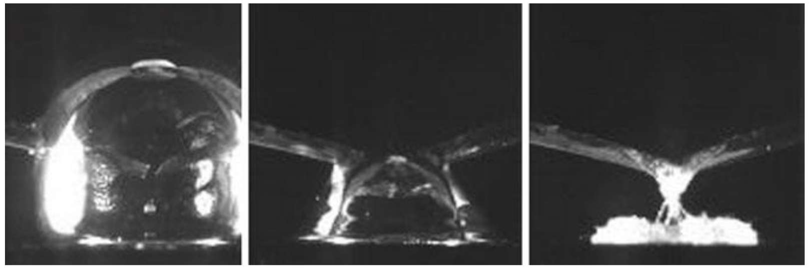
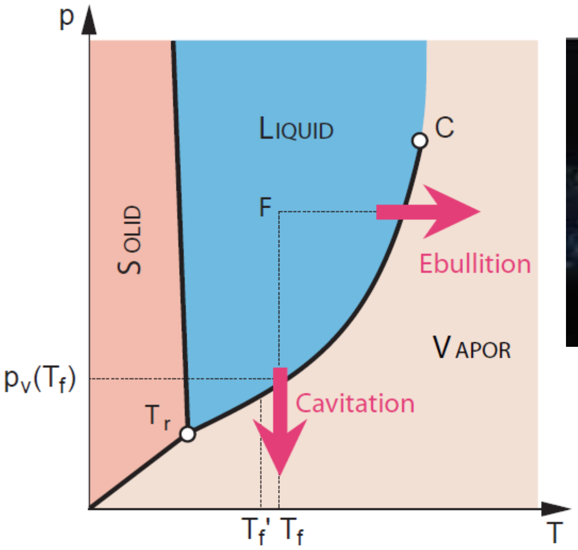
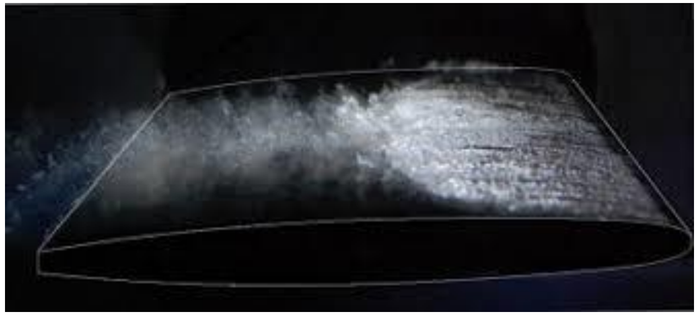
Introduction

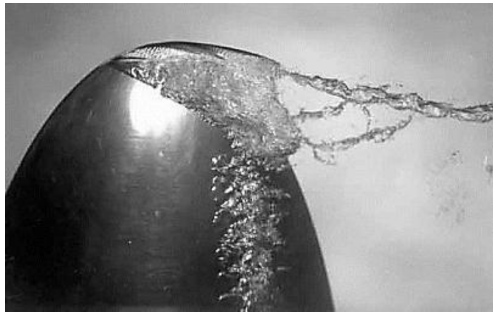


- Cavitation is 2-phase flow with phase transition driven by pressure gradients





- Different cavitation types can be distinguished:
  - Bubble cavitation
  - Attached or Cloud cavitation
  - Vortex cavitation



- Main problems are:
  - Noise
  - Vibrations
  - Material removal -> erosion
  - Performance impairment

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Introduction

There is a large variety of engineering processes and applications where possible mechanisms triggering local static pressure drop responsible for the initial evaporation can be identified:

- Propellers for marine application
- Sudden restrictions in pipes or ducts
- Control valves’ plugs or cages
- …
- Suction impeller of centrifugal pumps
- Stationary components of centrifugal pumps

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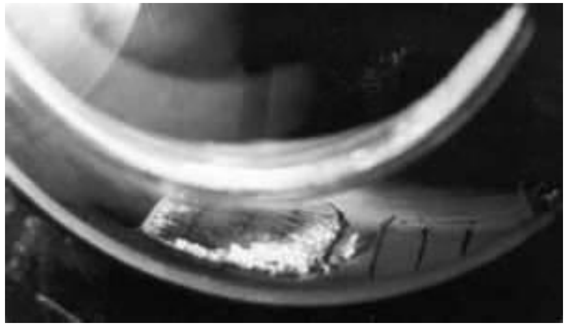
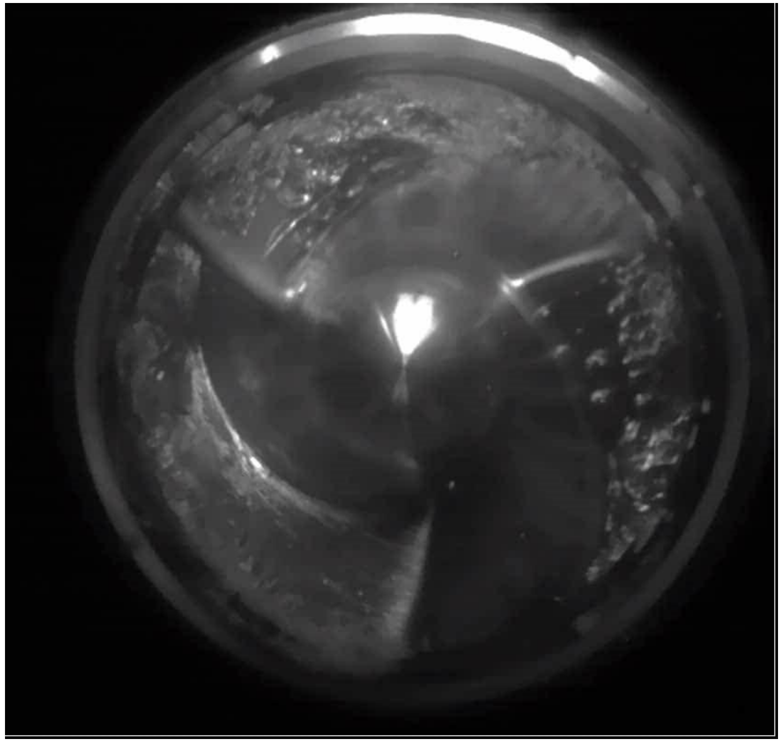
Cavitation in centrifugal pumps – Impeller

- Zone of lowest pressure in a pump impeller is close to the leading edge
- Depending on operating point (part load or overload) cavitation forms close to the impeller blade either at visible or not visible surface
- Part load caviation can be visually observed in specific test machines





Source: TU Darmstadt, Institute of Fluid Systems

Cavitation in centrifugal pumps – Stationary components

- ***Downstream***

Under certain conditions local static pressure can fall below vapor pressure even *after* the rotating component has imparted mechanical energy to flow stream!

Why is cavitation on stationary components of pumps relevant?

- Limitation of the operation envelop for small specific speed hydraulics due to cavitation at diffuser or volute channel(s) throat at overload
- Heavy erosion for high energy pumps when operating at part load usually close to their minimum continuous stable flow
- Performance impairment

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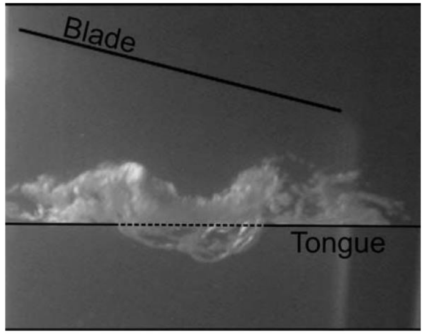

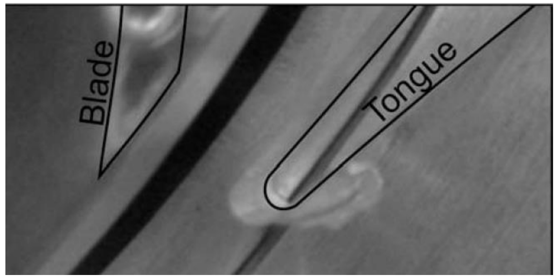

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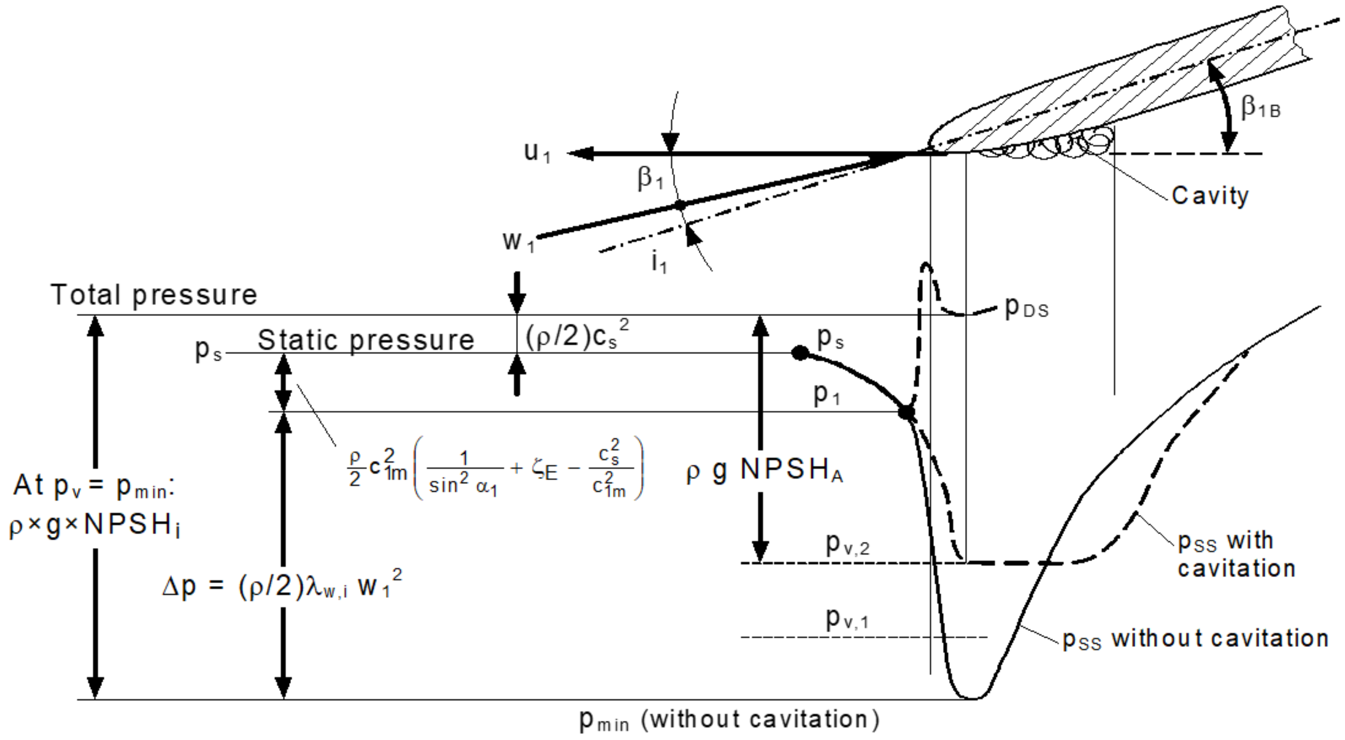
Impeller: flow condition at inlet

Approach flow and pressure distribution

- Difference between blade angle and flow angle causes changes in pressure distribution
  - Positive incidence (at part-load and design point) yields reduction in pressure at suction surface
  - Negative incidence (at overload) moves pressure minimum to pressure surface
  - If pressure drop is sufficient, fluid will evaporate



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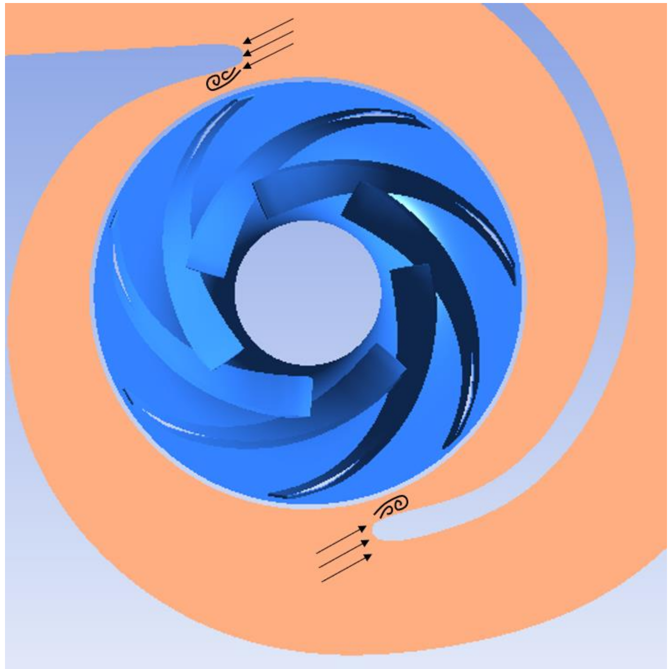
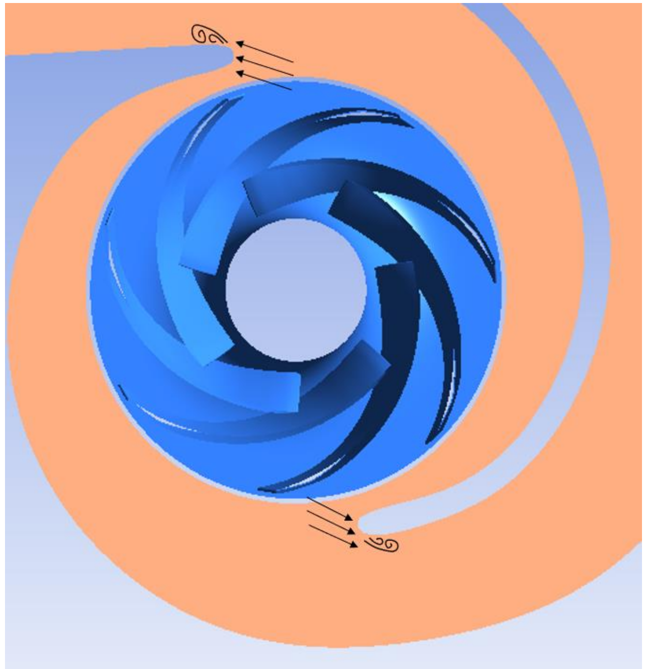
Stationary components: cavitation & off-design

Cavitation in stationary components tends to manifest more predominantly in off-design conditions, i.e. at flow rates smaller and/or larger than Best Efficiency Point

Physical mechanism triggering cavitation is mostly incidence due to change in *absolute flow angle* with changing pump's flow rate, however:



- Partload is usually associated with impeller recirculation (1D approach for analysis not possible!)
- Overload operation does not come with recirculation (allows for simplified approach)



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How does it manifest?

Typical indicators of pump cavitation include:

- Deteriorated suction capability → Head generation
- Enhanced secondary flow structures / vortices → Vibrations
- Erosion → Component life

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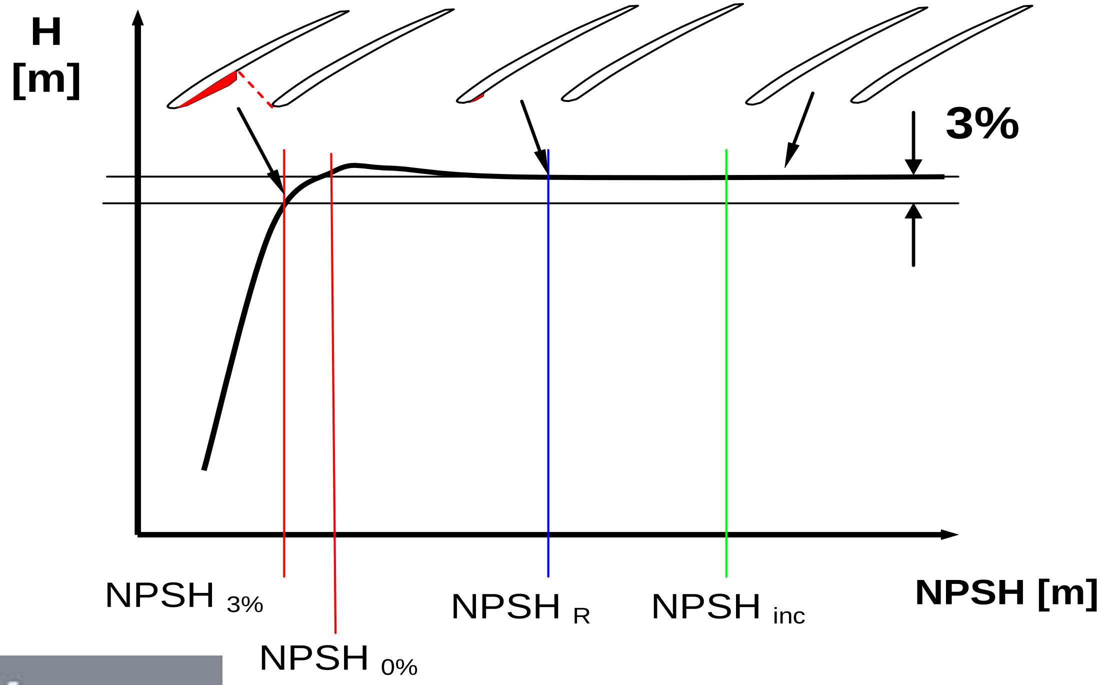
How does it manifest?

- ***Suction capability / Head generation (impeller)***

- Inception
  - First appearance of cavitation bubbles
  - Defined when ~ $Lc/D_2 = 1\%$
- Head impairment
  - 0%, 1% or 3% head reduction
  - Usually, 3% is used due to simplicity of measurement
  - 0% very difficult to estimate
- Full
  - Sudden head drop, no further reduction in suction pressure possible
- Recommended
  - OEM defined value for safe operation



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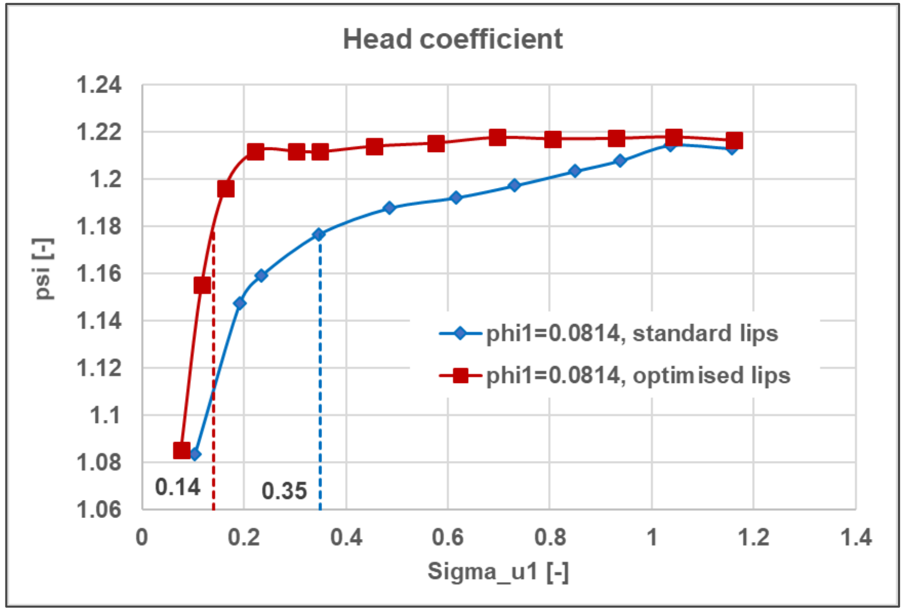
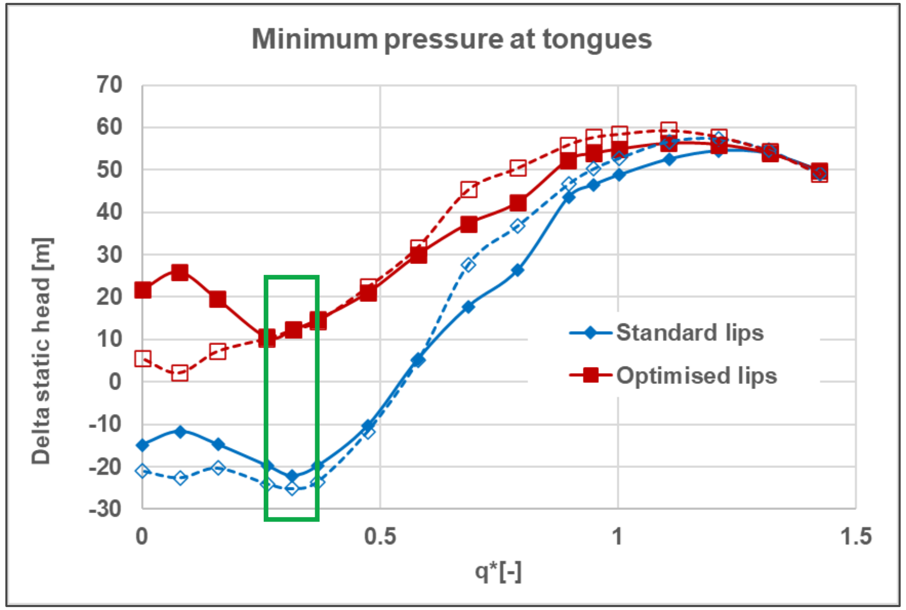
How does it manifest?

- ***Suction capability / Head generation (stationary components)***



Suppression of casing cavitation at one specific flow (partload operation, q*=0.35)

Effect on other flow rates: minimum pressure higher in the whole operating range



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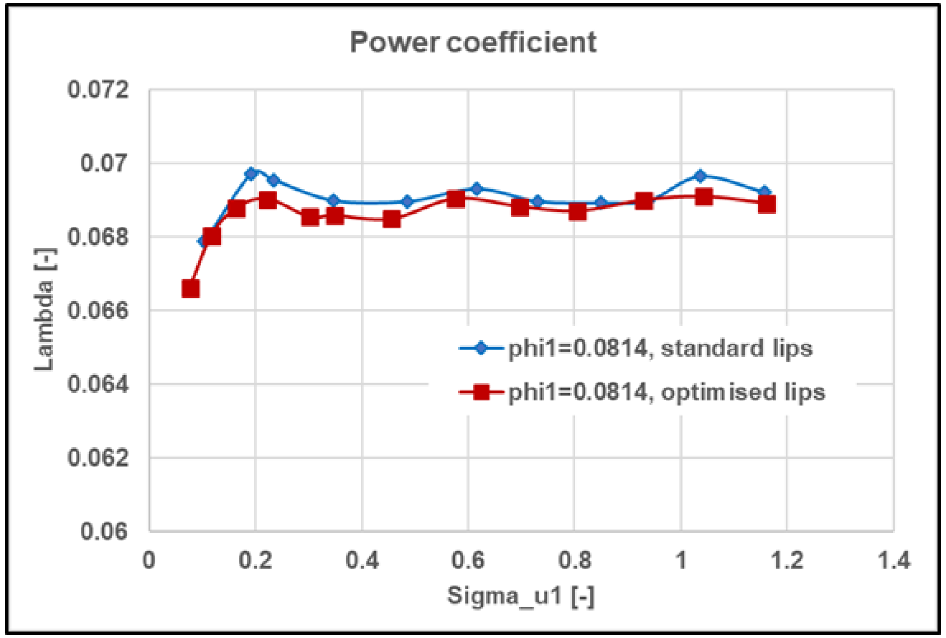
How does it manifest?

- ***Suction capability / Head generation (stationary components)***

- What is actually causing the head drop
  - Increased hydraulic losses
  - Reduced mechanical work imparted by the impeller to the fluid
  - *Combination of both*

- Absorbed power indicates the predominant aspect is the reduction of mechanical work (so concerning the *kinematics* of fluid flow)



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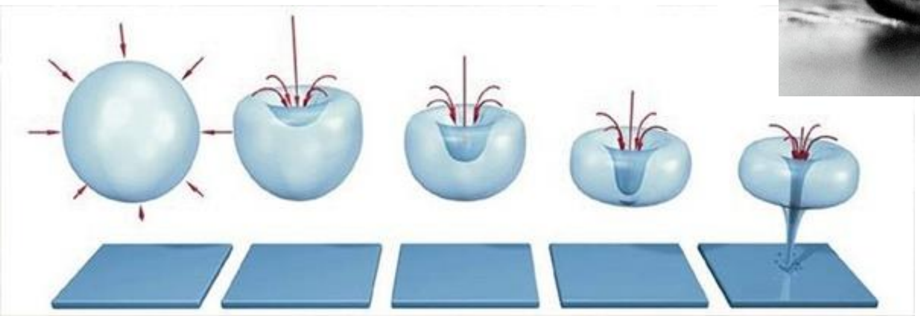
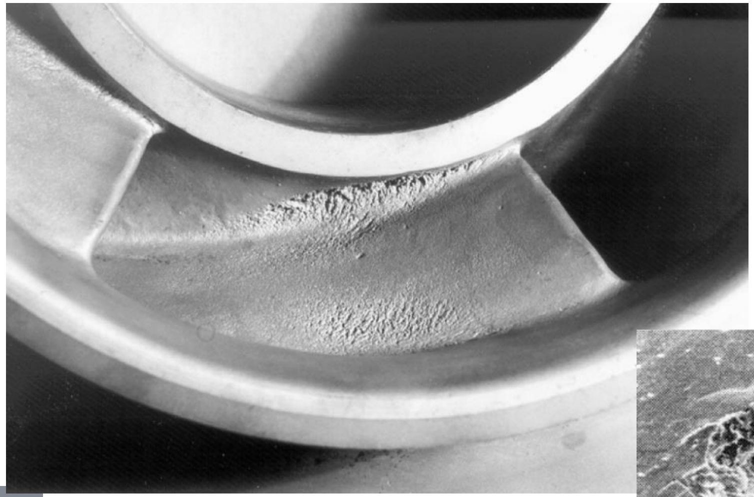
How does it manifest?

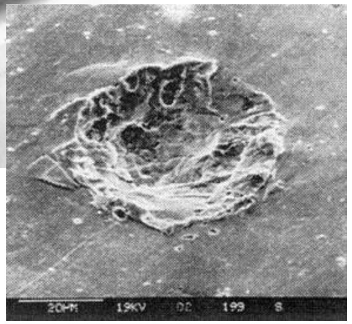


- ***Erosion (physics)***
- Cavitation erosion is due the collapse of bubbles or bubble clouds in the vicinity of a solid surface

- One hypothesis is that the erosion is due to a micro-jet formed during the collapse of bubbles

- Another hypothesis attributes the erosion to the shockwave associated to the bubble collapse





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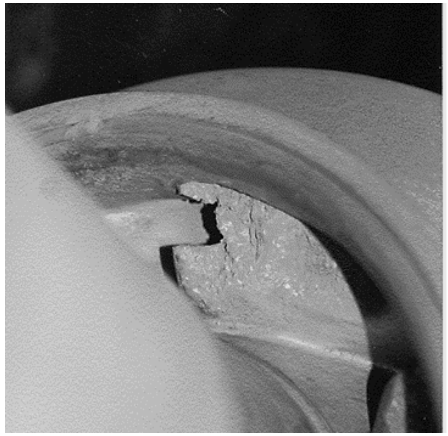
How does it manifest?

- ***Erosion (impeller)***
- Zone with highest erosion risk is usually the impeller eye
  - Pressure drop over profile inlet causes evaporation
- Erosion intensity depends on type of flow and operating conditions
  - Operating conditions determine location of lowest pressure
- Time until damage depends on energy density
  - U_1 used to assess cavitation risk



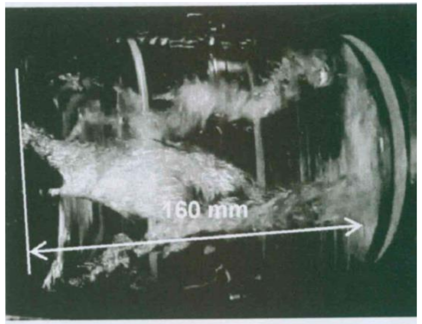
How does it manifest?

- ***Erosion (stationary components upstream)***

Characteristic partload phenomena include impeller inlet recirculation

When this special flow regime establishes, large low-pressure areas form and propagate way into pump’s suction casing

Cavitation may take place also at impeller’s eye wear ring due to sudden pressure drop of leakage flow through running clearances.



Source: Skara 2014, «Experimental observation of Cavitation Phenomena in Centrifugal Pump impellers at Part load, PhD Thesis

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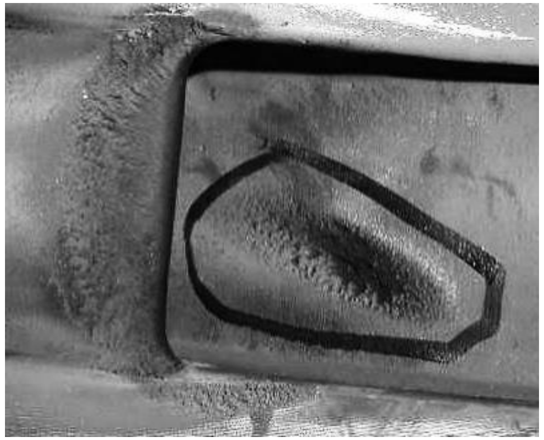
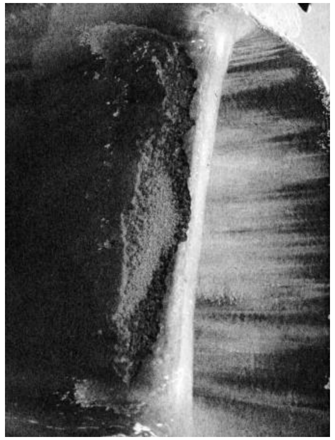
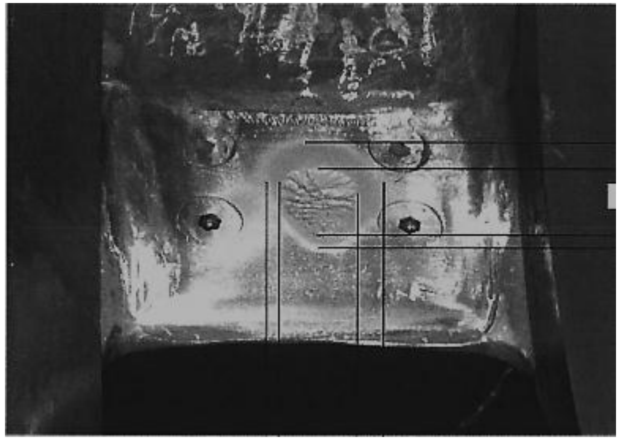
How does it manifest?

- ***Erosion (stationary components downstream)***
- Excessive part-load operation can effect other pump components



- Volute or diffuser cavitation
  - At very low part load, rotor stator interaction can lead to significant pressure drop at collector inlet
  - Additionally, vortices can occur



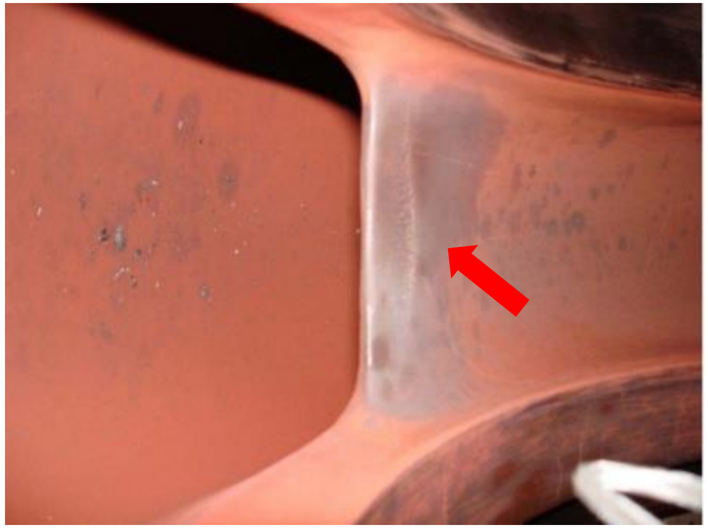


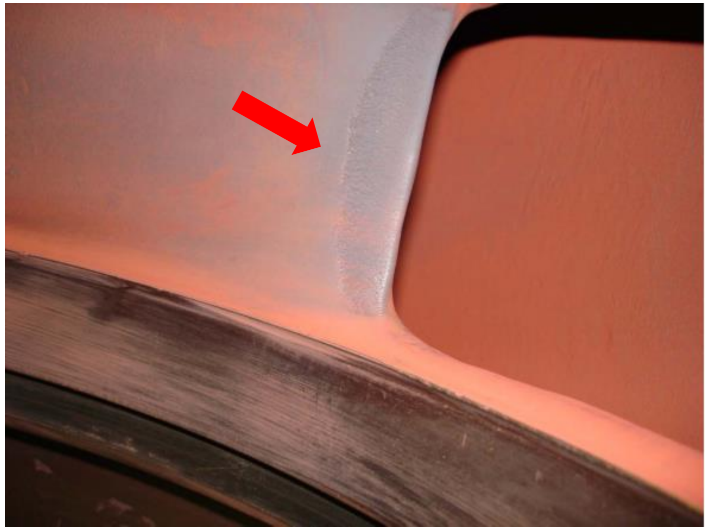
- These erosion problems are less common and generally attributed to excessive off-design operation

How does it manifest?

- ***Erosion (stationary components downstream)***

The imposion of cavitation bubbles caused by flarge flow incidence has a *much higher* erosive power when it takes place downstream the impeller, as the energy involved in the process is much higher





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How does it manifest?

- ***Secondary flows (stationary components downstream)***

Partload operation is intrinsically transient.

Perturbances originating from that (or those) vanes in stall condition propagate to adjacent vanes so inducing another stall.

This sequence of phenomena, well known in compressors, may trigger what is commonly referred to as *rotating stall*, here coupled with vortex formation.

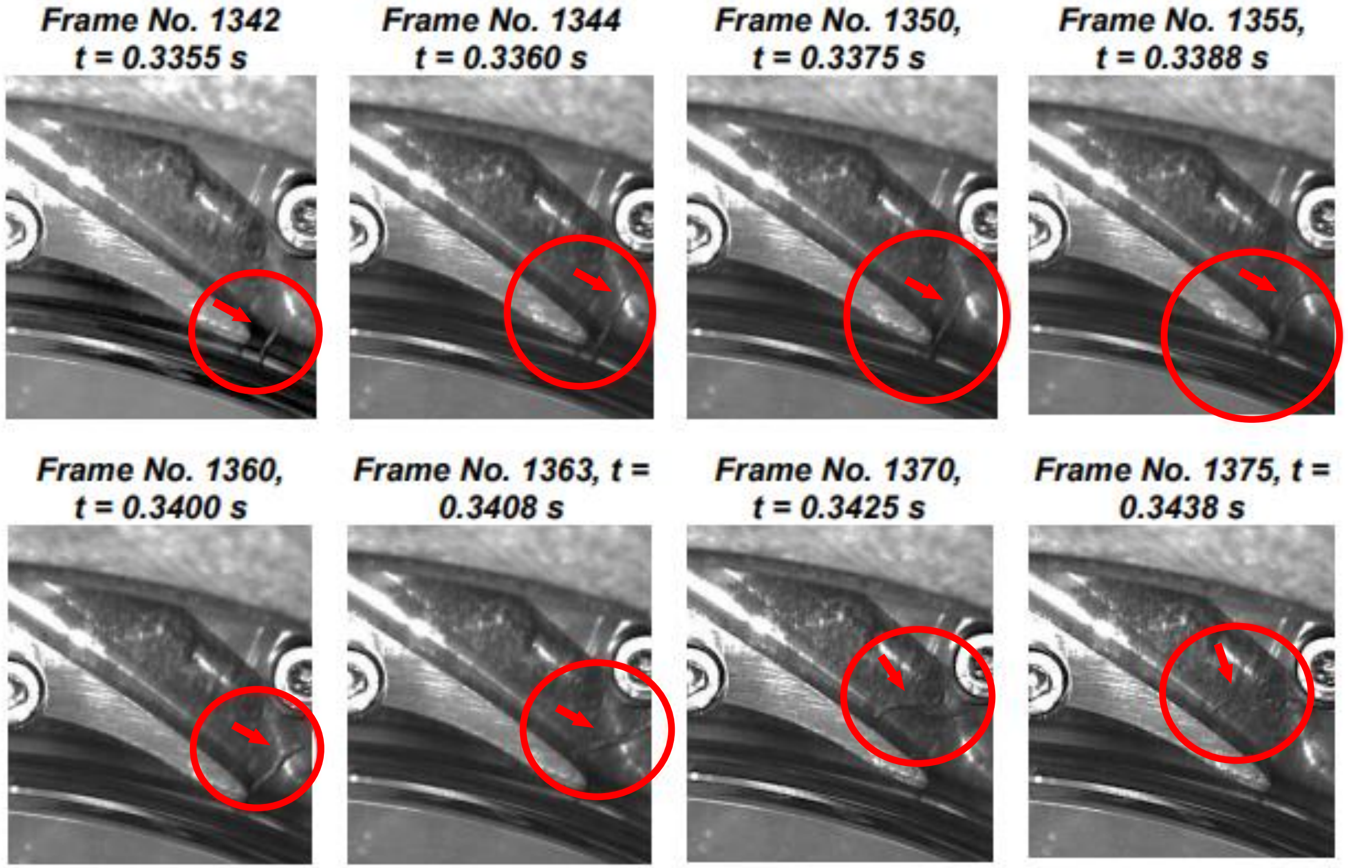

Figure 5: Evaluation of a cavitating vortex in diffuser channel (q = 0.4)*

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Analysis and remedies

- ***Testing***

- N(et) P(ositive) S(uction) H(ead) represents the difference between absolute suction head and vapor pressure expressed as head

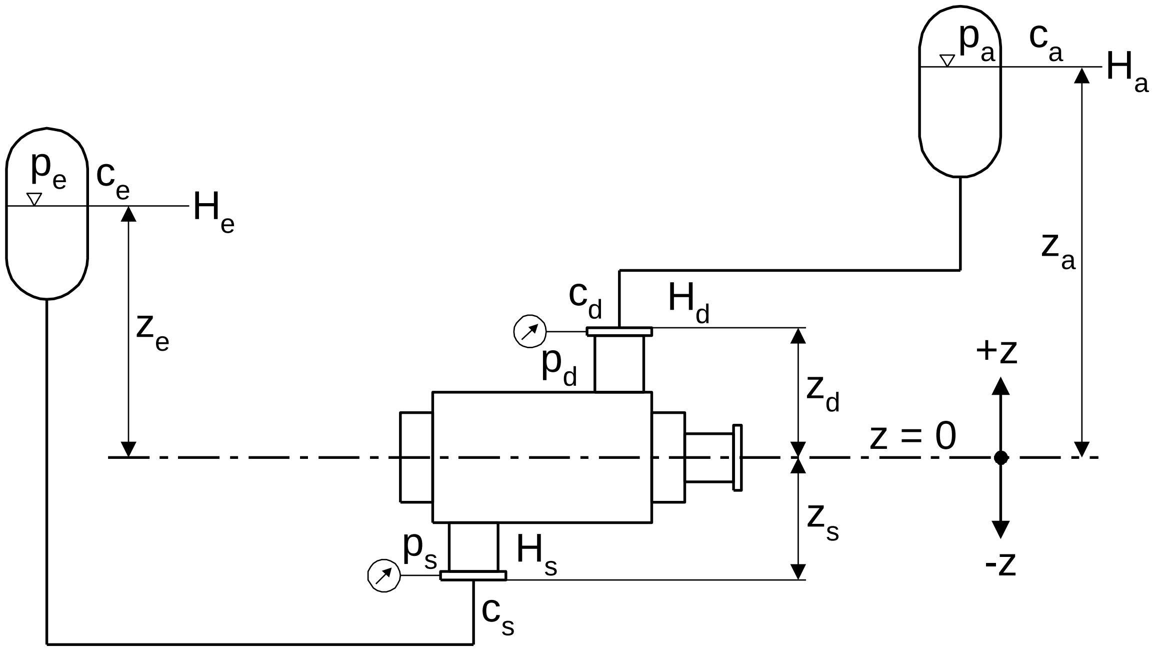
$$H_V = \frac{p_V}{\rho \cdot g}$$

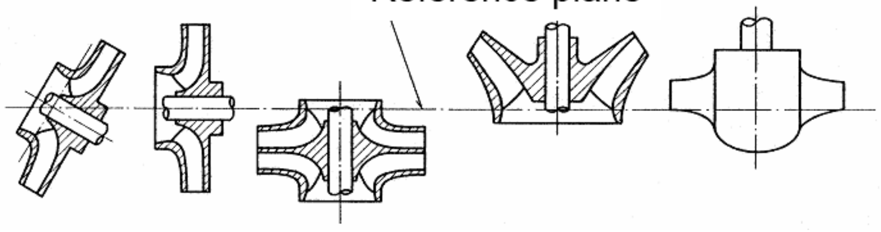
  - Definition for pump:

$$NPSH = \frac{p_{s,abs} - p_V}{\rho \cdot g} + z_S + \frac{c_S^2}{2g}$$

  - Definition for installation:

$$NPSH = \frac{p_{e,abs} - p_V}{\rho \cdot g} + z_e + \frac{c_e^2}{2g} - H_{V,S}$$





Analysis and remedies

- ***Testing***

- Standard tests
  - Assessment of NPSH values at different flow rates
  - Establishing NPSH curves for 3% head drop

- Advanced tests
  - Bubble observations to establish cavitation extend at different suction pressures
  - Cavitation noise measurements to assess cavitation inception at impeller pressure surface

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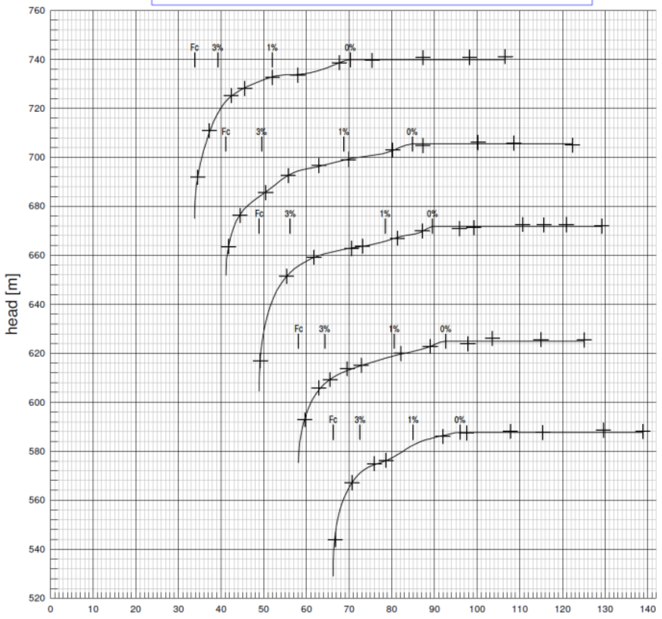
No. de commande :	207 0038	Vitesse :	4879 [rpm]
Client :	EDF CNEPE	Densité :	992.3 [kg/m3]
Projet :	EPR Flamanville 3	Température :	40.00 [°C]
Fonction de la pompe :	Pompe alimentaire	Débit :	3506.0 [m3/h]
Type de pompe :	HPT 470 d	Hauteur :	668.00 [m]
Tag No. / Pompe No. :	3150 PO / 207 0038/6	Puissance :	7450.00 [kW]
Diamètre 1ère roue :	0.4710	Rendement :	85.00 [%]
Diam. roue suivante :	-	NPSH 3% :	58.50 [m]

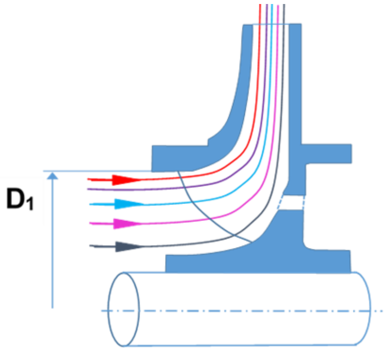
Flow [m3/h]	Head [m]	Npsh 0% [m]	Npsh 1% [m]	Npsh 3% [m]	Npsh Fc [m]
2557.8	739.82	70.31	51.96	39.22	33.75
3142.9	705.47	84.77	68.71	49.44	41.14
3505.2	671.88	89.56	78.42	56.16	48.89
3906.6	624.92	92.66	80.52	64.29	58.13
4219.1	587.70	96.00	85.01	72.56	66.23

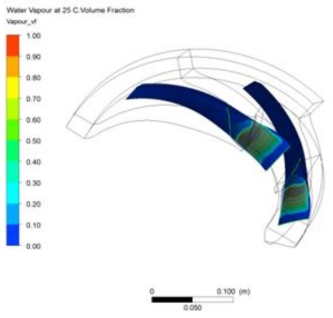


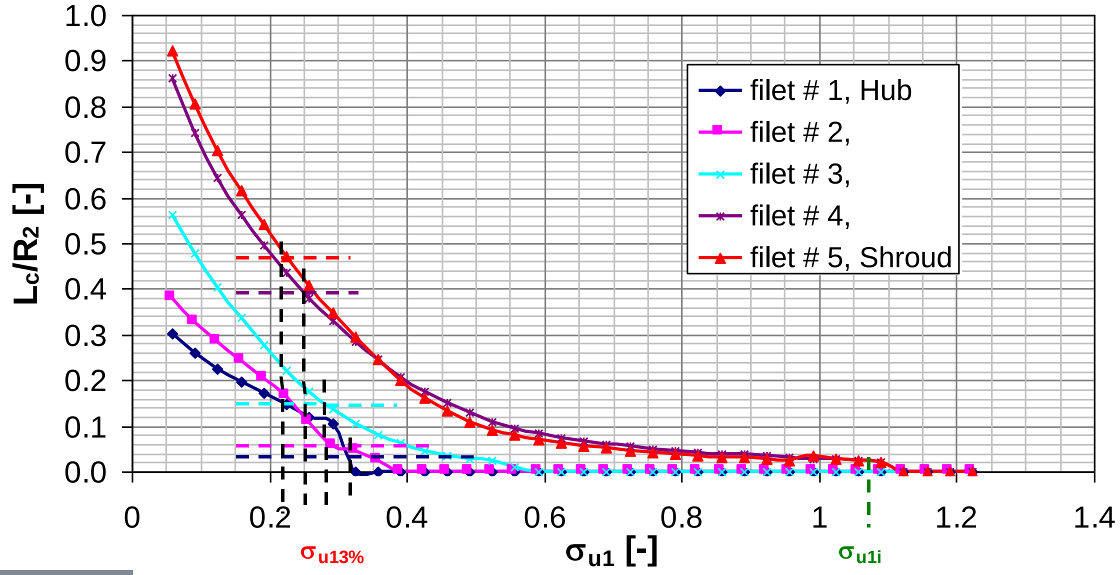
Essais effectués par	En présence de	Date	Procès-Verbal N°
L. Millet		23 Jul 2014	4.137.044.404.341

Analysis and remedies

- ***Cavitation modeling in modern CFD codes***
- Criterion for cavitation inception
  - First bubble explosion not visible
  - Small cavities very much influence by the water quality
  - Cavitation Inception: Lcav/D2 = 0.01
- Criterion for head impairment
  - Head impairment prediction using calculated head with CFD using cavitation model is not very stable
  - The head impairment is assessed from bubble length or blockage of the cavity in the blade-to-blade throat area







Analysis and remedies

- ***An example of CFD validation***
- Boiler feed pump retrofit project for a Combined Cycle plant
- Pump selected for cavitation free operation
  - Existing suction impeller suffered of cavitation erosion on the suction side (visible side) of the vanes
  - New impeller design has allowed a cavitation free operation for a cavitation number equal to $\sigma_{U1} = 0.5$
  - Very good agreement between simulation and experiment for inception at suction surface

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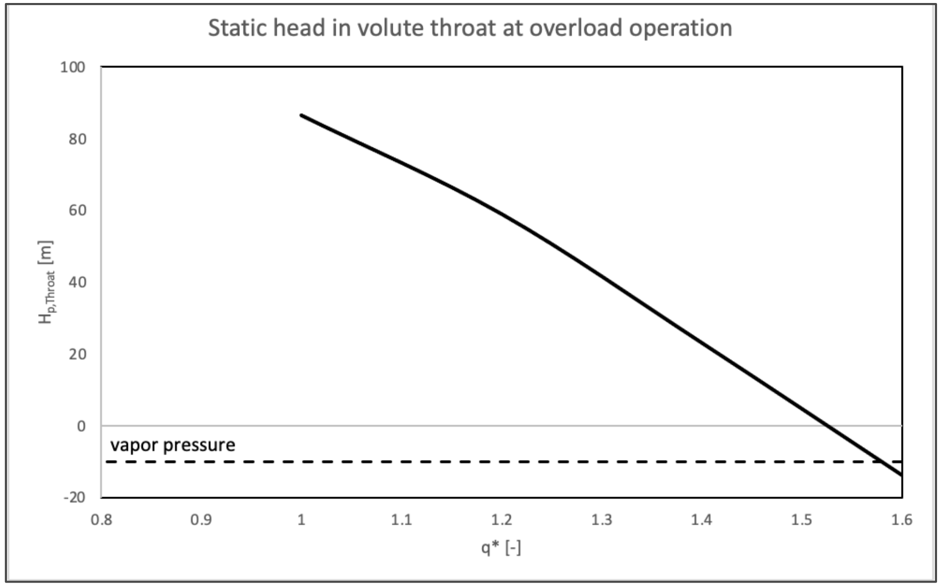
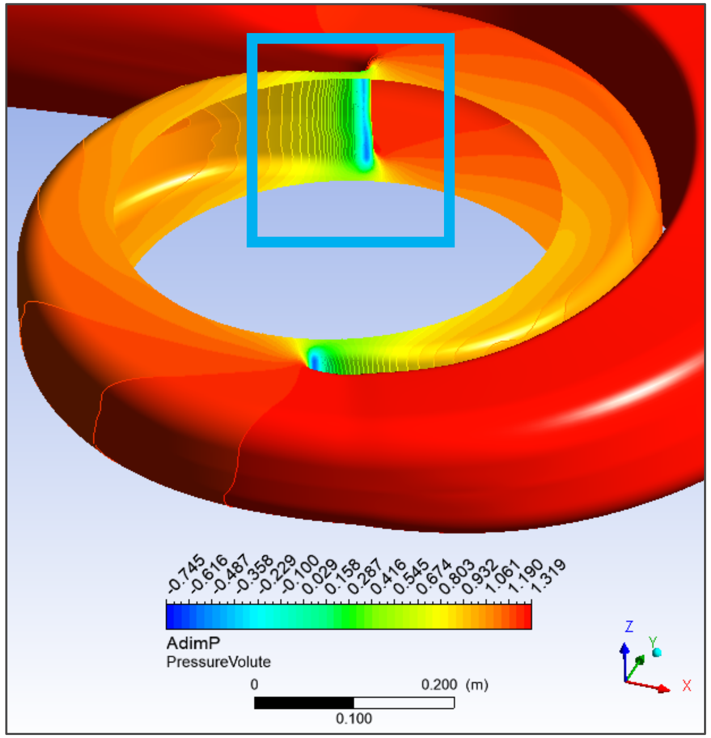
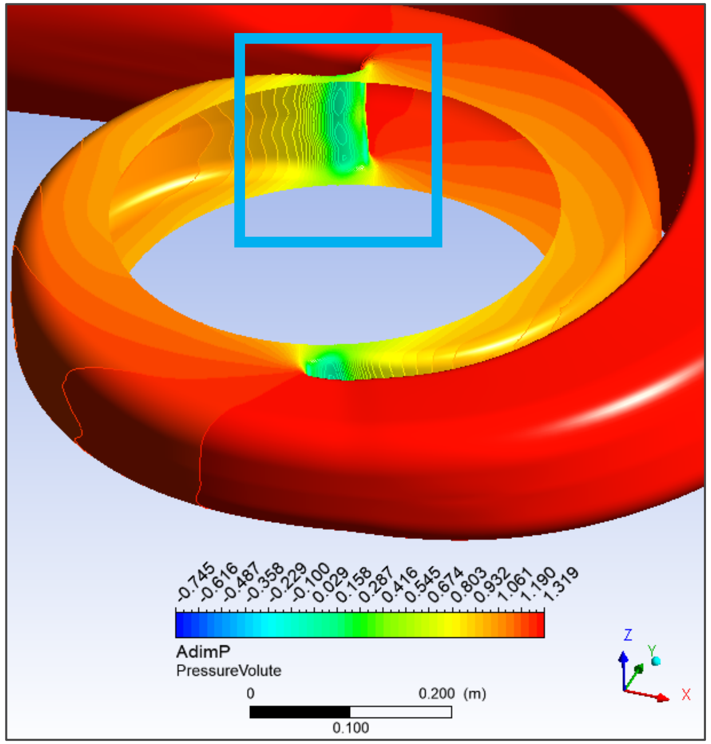
Analysis and remedies

- *1D approach*



- *CFD (1-phase or 2-phases)*





Analysis and remedies

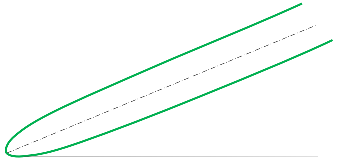
- ***Impeller design***
- Suction impeller can be designed either for **low $NPSH_{3\%}$** (high Nss) or **low $NPSH_i$**

- Each option will result in different designs and cavitation behavior

low $NPSH_{3\%}$

σ_i = 1.2 to 2

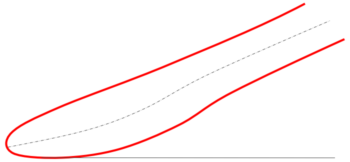
β_{1a} = 10 to 15°



low $NPSH_i$

σ_i = 0.5 to 0.8

β_{1a} = 14 to 18°



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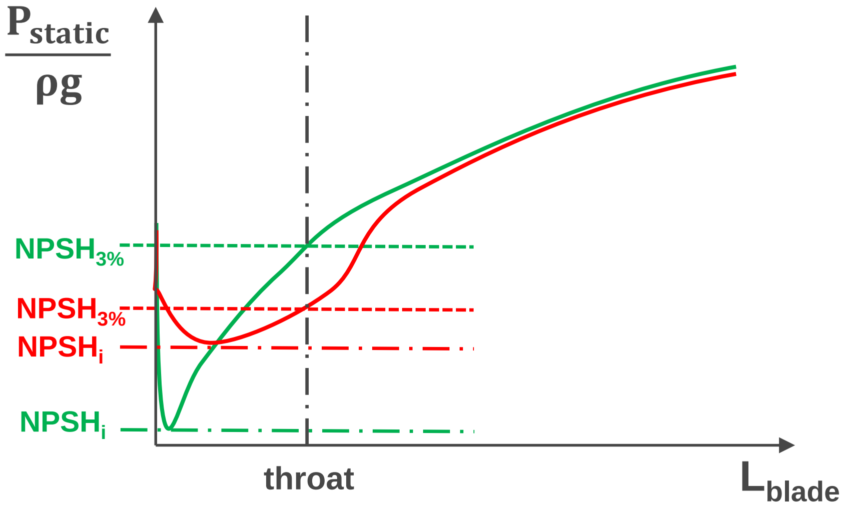
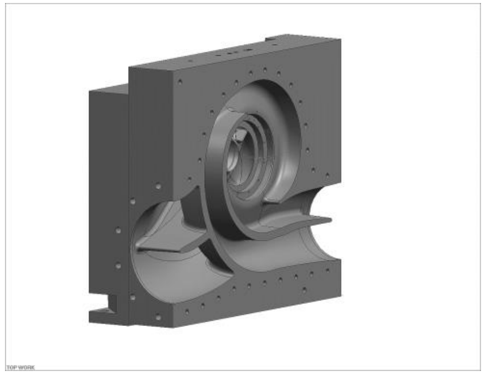
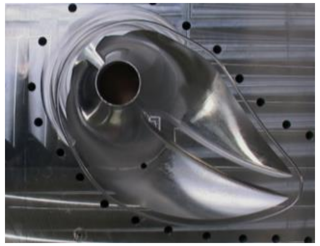
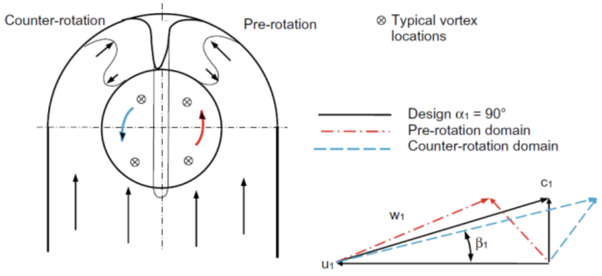


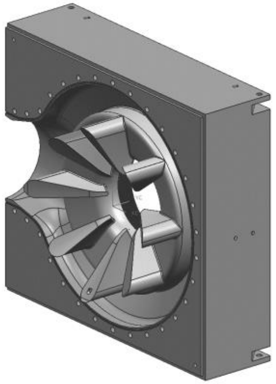
Analysis and remedies

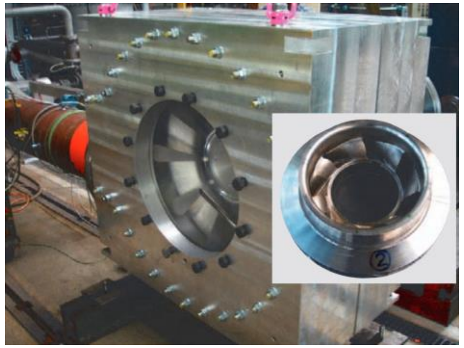
- ***Inlet case design***
- Classical inlet casings for multistage boiler feedpumps
  - Suction casings of between-bearing pumps produce strongly non-uniform fully 3-dimensional flows to the impeller. Consequently incidence, cavity length and bubble volume vary over the circumference.
- Optimized suction casing for multistage barrel pumps
  - Inlet vanes ensure uniform, axial inflow to suction impeller
  - No incidence variation over circumference











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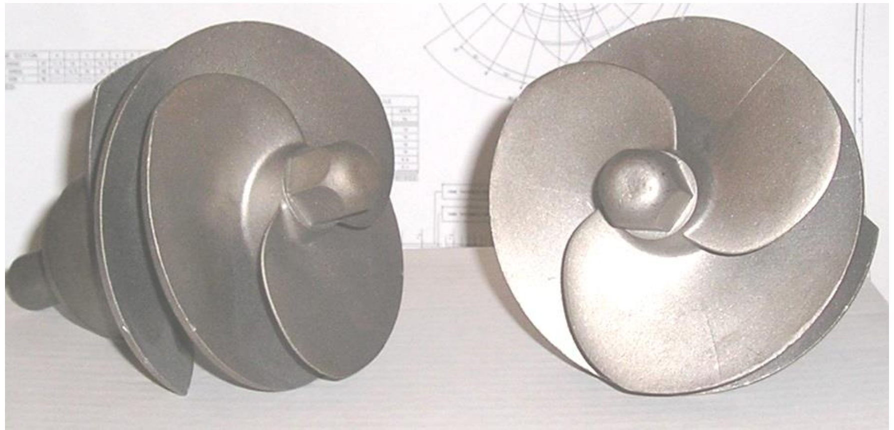
Analysis and remedies

- ***Inducers***
- Inducers are axial geometries installed in the eye of an impeller
- They are able to generate head in the presence of significant cavitation
- It is possible to increase the achievable NSS for an industrial pump up to values of Nss = 300 to 450



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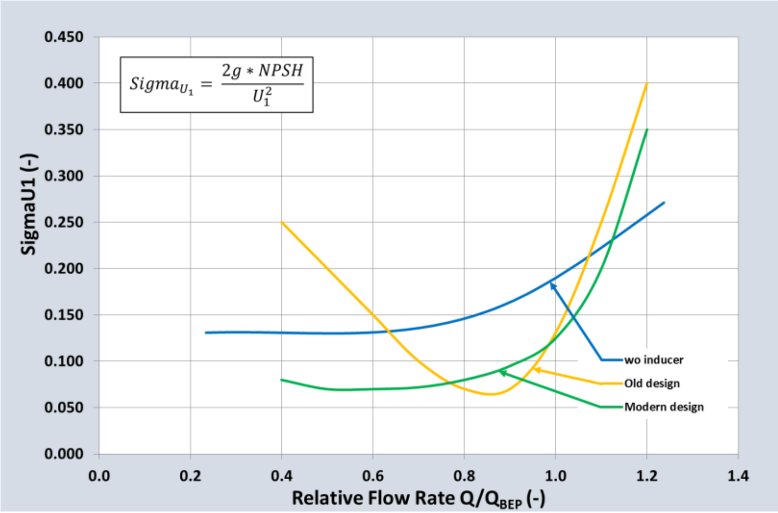
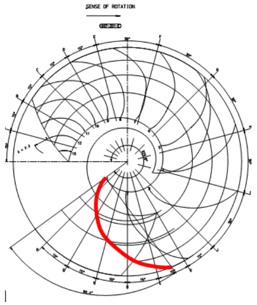
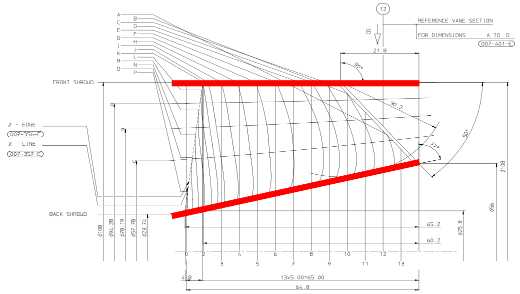
Analysis and remedies

- ***Inducer design***
- Modern inducer designs allow an improved suction capability on a much larger operating range
  - No improvement to be expected at high flows
  - Selection needs to account for maximum flow rate



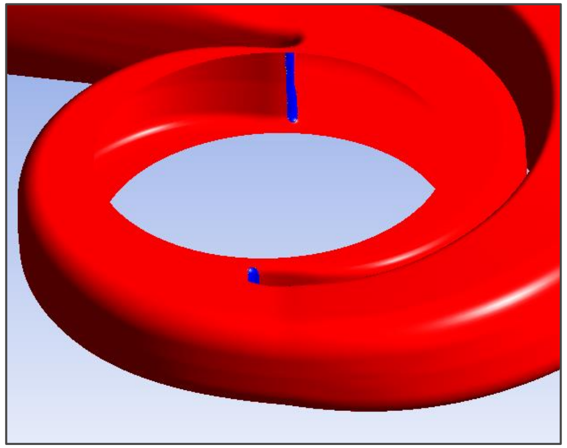


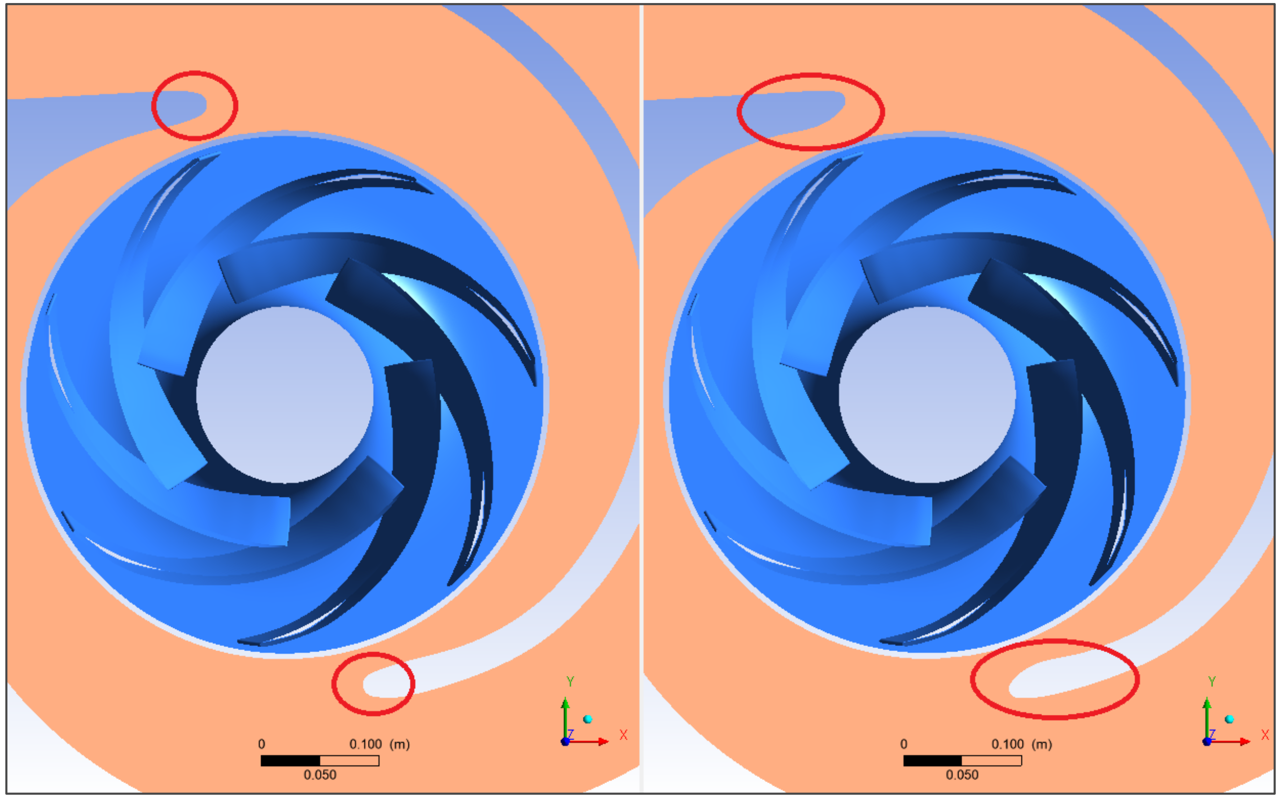


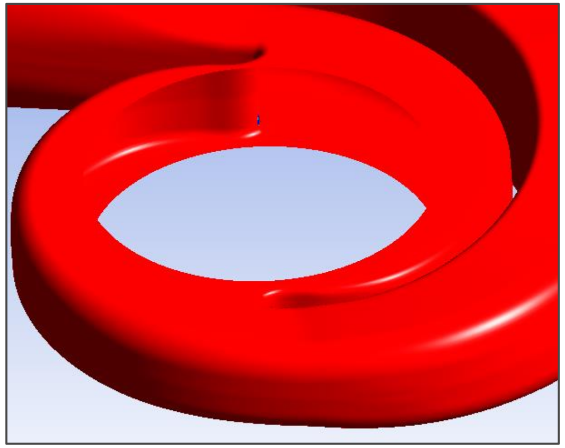
- Design characteristics
  - Convergent meridional shape
  - Strong sweep back of the inducer leading edge
  - Variable blade angle

Analysis and remedies

- ***Volute lip profiling***







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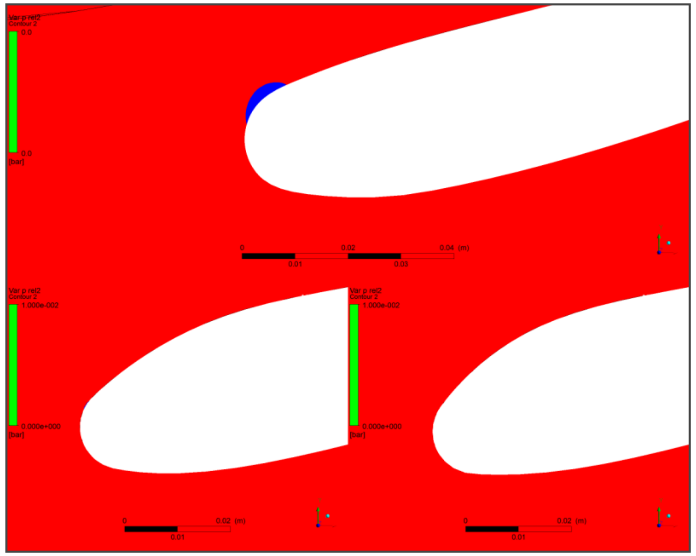
Analysis and remedies

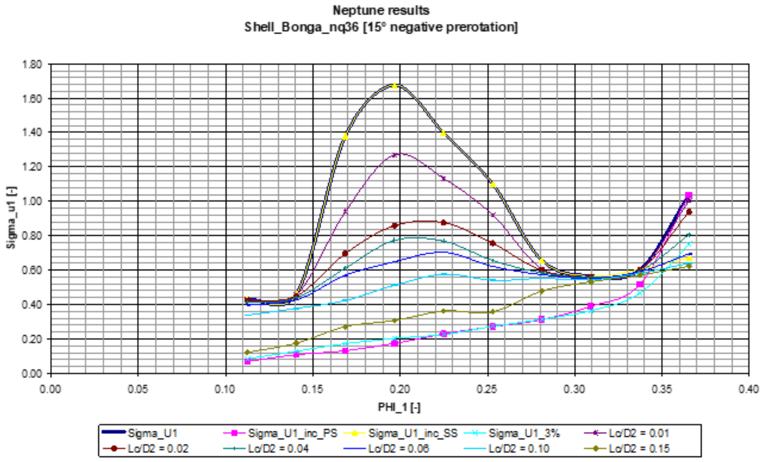
- ***Experimental investigation***

- Model pump
- Internal pressure measurement
- Interchangeable lip insert to allow for direct comparison of different profiles
- Validation of numerical techniques



Analysis and remedies

- ***Estimation of erosion damage & component life***
- Customers often request an assessment of expected component’s life under prescribed conditions
  - Possible operation history sampled accordig to time
  - Expected bubble length estimated using CFD
  - Cumulative damage assessed
  - Expected residual life time calculated from erosion rate: Sulzer method is based on empirical correlations derived from internal experience and ASTM test standards (ASTM G-32 and G-134)



Calculation Handbook Volume 1				SULZER
Erosion rate from cavity length				
3	Author:	for extention and reorganis. DSz 26.03.2003		
4	Basis:	Gü 11.08.1997	Validation:	
5	Operator	DuP	Date:	
6	Plant:	Validation	Rev. 2	
7	Pump type:	HPDM	Rev. 3	200000 bbl/day
8	f_q	Double suction : 2 , Single suction : 1		1
9	Q_{opt}	Q total at bep	m^3/s	0.3299
10	Q	Q total at operation point to be analysed	m^3/s	0.3681
11	$q^* = Q/Q_{opt}$	flow rate ratio	-	1.12
12	z_{La}	number of blades	-	7
13	n	shaft speed	rpm	5602.5
14	D_2	Suction impeller, outer diameter	m	0.3150
15	D_1	suction impeller, eye diameter	m	0.1997
16	D_n	suction impeller, hub diameter	m	0.1199
17	E_B	blade thickness at Lcav	mm	6.18
18		**Material**		Duplex
19	R_m	tensile strength	N/m^2	6.55E+08
20	E	Young's modulus	N/m^2	2.00E+11
21	U_R	ultimate resilience	N/m^2	1.07E+06
22	F_{mat}	see 1.008.004, table 1	-	1
23	F_{cor}	see 1.008.004, table 1	-	1.5
24		**Liquid**		water
1 25	T	actual plant	°C	30
26	T	used for calculation (FT = 1.0 for T<60 °C)	°C	60
27	ρ	liquid density	kg/m^3	1030
28	α	gas content (*!! has a large influence on erosion*)	ppm	24.000
29	F_T	temperature factor	-	1.0000
30		**NPSH situation**		
31	NPSHav	NPSH available	m	123.9
32	u_1	circumferencial velocity at D1	m/s	58.6
33	c_{1m}	meridional velocity at So	m/s	18.4
34	σ_{av}	available cavitation coefficient	-	0.71
35	$\sigma_{av\,recommended}$	recommended available cavitation coefficient	-	0.59
36		check NPSHav		**ok**
37	$p_1 - p_v$	absolute inlet pressure, calc with NPSH av	N/m^2	1.08E+06
38		**Prediction from L-cav on suction side**	Lcav %	5%
39	Lcav (ss)	Max. cavitation length on suction side	mm	15.750
40	$P_{ER\ theoretical}$	Theoretical specific erosion power $E_R x U_R$, table 6.1	W/m^2	3.668E-05
41	$P_{ER\ real}$	Real specific erosion power	W/m^3	2.416E-05
42	ER	Erosion rate	m/s	2.25E-11
43	**ER-1000**	**Erosion rate in mm per 1000hrs**	**mm/1000h**	**0.08**
44	E40	Erosiont rate mm per 40'000 hrs	mm	3.2
45	L_{sf}	Requested (specified) impeller life	hours	40000
46	L_{erw}	Expected impeller life	hours	**38114**
47	W ? 0.96	Probability to reach specified impeller life	-	0.01
48	p_i	Implosion pressure from cavity length 6.1.16	N/mm^2	29
49	$p_{i,ES}$-min	Min. Erosion threshold value, table 6.1.17	N/mm^2	35
50	$p_{i,ES}$-max	Max. Erosion threshold value, table 6.1.17	N/mm^2	98
51		Is pi (existing) > pi.ES-min (allowed)	-	no
52		Is pi (existing) > pi.ES-max (allowed)	-	no
53		Evaluation of cavitation risk	-	high risk

Conclusions

- Cavitation is a well-known phenomenon, it’s one of the primary issues associated to centrifugal pumps’ design and operation.
- Typically, impellers are the components most affected by cavitation. However, although rather counter-intuitive, cavitation in centrifugal pumps’ stationary components may take place also *after* mechanical work is imparted to fluid stream
- It may manifest in different ways: erosion, noise, instability, secondary flows, vibration, head generation etc.
- Generally, off-design conditions are more prone to manifesting casing cavitation
- Experimental evidences confirm all of the aforementioned symptoms
- This phenomenon can be analyzed with different approaches, simple (1D calculation) or complex (CFD, including 2-phase models)
- Fine tuning of impeller, suction, volute or diffuser may lead to drastic reduction of cavitation risk

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Thank you for listening!

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