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WATER CENTRIFUGAL PUMP, DESIGN AND FLUID FLOW ANALYSIS

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Abstract: In this article we have designed the active parts of a centrifugal pump (volute casing and impeller) often used in the naval field, especially for ballasting installations of commercial shipping vessels. Data on dimensions, geometry and mode of operation were used from specialized technical documentation and the works of other authors. The design of the volute casing and impeller assembly was done with NX SIEMENS. The study of the fluid flow was done with ANSYS CFX by importing the whole, some conclusions were drawn regarding the fluid velocities and the pressure field. The influence of the cavitation phenomenon was taken into account by modelling this phenomenon, thus avoiding the appearance of the minimum negative pressures field. It is known what is the adverse influence of the cavitation phenomenon and what are the factors that can reduce the occurrence of this phenomenon.
Key words: centrifugal pump, fluid flow analysis, cavitation, NX Siemens, ANSYS CFX.

1. INTRODUCTION

In naval piping installations, centrifugal pumps are used to transport water in ballast, bilge, fire extinguishing, water supply, and cargo transfer facilities at oil chemical tankers [1]. These pumps are built for medium flow rates (0.5-1 m^3/s) and low and medium pressures (up to 9 bar), and are used for the transfer of slightly viscous liquids.
Centrifugal pump is the most common of all construction types currently available in world being used in the field of relatively low flow rates and high pressures. This trend is due to both the constructional simplicity of the centrifugal pump and lower operating costs. Also, by using drive engines with high speeds, it was possible to obtain values of the discharge pressure which previously could not be obtained only with piston pumps. The main hydraulic elements that make up a centrifugal pump are:

- the impeller;
- the volute casing.

1.1. Centrifugal pump operation

The operation of the pump is simple and consists in driving the pump shaft by an electrical engine. The impeller is fixed to the shaft and it will perform a rotational movement. Any particle of liquid that is in contact with the impeller, it will be projected to its periphery due to the centrifugal force what acts on it. The role of the impeller' blades is to direct the path of the liquid particle in this way so that, at the exit of the impeller, it has a kinetic energy that can be transformed then in potential pressure energy [2].
At the exit of the impeller, the liquid particle is collected in the volute casing, and from here onwards is directed to the discharge line. It's done thus a displacement of the liquid particle from the inlet to the impeller to the discharge port of the pump. The same principle applies to a compact mass of liquid, which, under the action the same centrifugal force, traverses the path to the suction port of the pump and the discharge, making a continuous circuit and thereby the pumping phenomenon.
A centrifugal pump to be able to operate, the fluid must be in constant contact with the impeller from the beginning of its rotation, otherwise the displacement of the liquid can no longer take place.
The angular velocity of the pumps has constantly shown an increasing trend, offering the advantage of a small pump size, but it can't exceed certain limits conditioned by the mechanical strength of the material from which the impeller is made. Today there are pumps with angular velocity between 6000-7000 rpm in the world, but it should be noted that a too high angular velocity also has the disadvantage of worsening the suction conditions of the pump, with all adverse consequences for the installation. Electrical engine driven pumps are usually directly coupled and driven at their rated speed.
The size of the impeller diameter is also limited due to the size of the pump, which can lead to unreliable dimensions. Thus the maximum values of the discharge height that can be obtained by a single-stage centrifugal pump at standard angular velocity operating, is located within 180-200 meters column of pumped liquid.
To achieve higher pressures without improving

angular velocity or diameter of the impeller, the solution is used with several impellers mounted in series. Pump centrifugal, whose construction has impellers placed in series, is called "multistage", considering that each impeller represents single stage.
In order to characterize the operation of centrifugal pumps it is necessary to introduce some quantities to quantify the amount of liquid passing through the pump, the energy exchange it has place in the pump as well as its efficiency. In the case of all hydraulic machines these sizes, also called functional parameters are [3]:

- flow (Q) [m^3/s];
- height of pumping (H) [mcol H_2O];
- absorbed power (P_a) [KW, HP];
- efficiency (η);
- angular velocity (n) [rot/min].

A centrifugal pump driven at an engine speed (angular velocity) can operate in one installation pump with different flow rates and appropriate pumping heights, depending on which it also modifies the absorbed power and efficiency.
The pumping height (H) represents the energy transmitted by the pump to the unit of liquid gravity (1N – 1newton) between inlet and outlet. Pump height (H) is calculated as the difference between hydrodynamic load (energy of the weight unit) at the outlet and hydrodynamic load at the inlet.
The pumping height (H) depends on the flow and the curve H=H(Q) is the load characteristic of the pump or internal characteristic (figure 2).

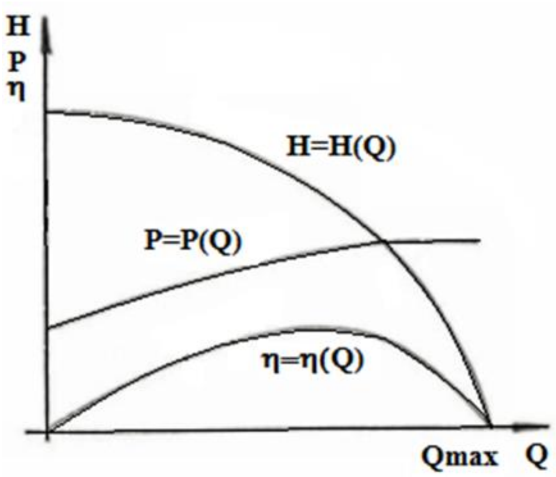

Fig. 1. Functional parameters [4]

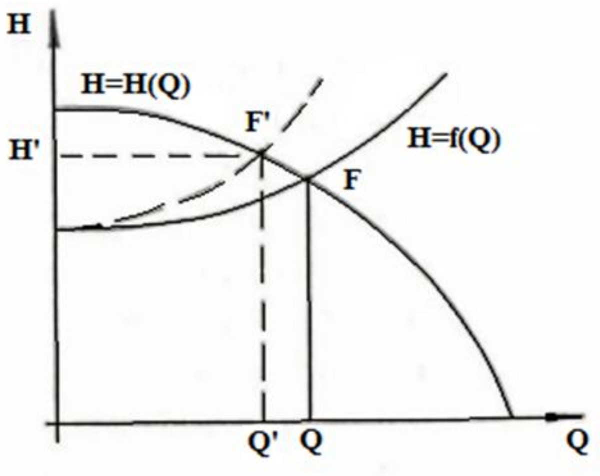

Fig. 2. Load characteristic of the pump [4]

The operation of the centrifugal pump in the system pipelines depends on the relationship between the functional parameters that can be a function of:

$$f\left(Q, H, P_a, \eta, n\right) = 0 \tag{1}$$

In the operation of the pumps the curves that are important are:

- the curves H= f(Q), for n=constant, called load curves;
- the curves P_a=f(Q), for n=constant, which expresses the variation of the absorbed power with the flow;
- the curves η=f(Q), for n=constant, these curves being important for knowledge of the behavior of the pump at different flows.

By drawing these curves results the universal characteristic of the pump (figure 1), which characterizes the operation of the pump at a certain angular velocity (n).
If on load characteristic diagram of the pump (internal characteristic) is also drawn the characteristic of the installation H=f(Q) (external characteristic), then at the intersection of the two curves find the operating point F (figure 2). By changing the characteristic of the installation (for example by operating a valve) point operation F moves to F' and the pump works at other parameters: Q', H ', P', η'.

1.2. Cavitation phenomenon

The flow regime of the fluids through the pumps favours the appearance of the cavitation. The essential parameter in the development of the cavitation is the pressure, which decreasing along to a minimum below the critical value of the fluid followed by an increase, it favours the appearance in the liquid of some cavities containing vapours of liquid and gases dissolved in liquid [5].
The appearance of the cavitation is also determined by the existence of solid particles in suspension and gases dissolved in the liquid. The amount of air dissolved depends primarily on temperature and is inversely proportional to it.
At pumps, if we consider the hydraulic circuit between suction and discharge, in a dynamic flow regime it is found that minimum pressures are registers in the area

of the impeller blades in the vicinity of the inlet zone. So this area will be sensitive to cavitation and in case the minimum pressure is below the critical pressure and there are cavitation germs, it starts immediately. The degree of development of cavitation depends on the difference between the critical and the minimum pressure at the impeller.

The effects of the cavitation phenomenon is grouped into [6]:

- Noise and vibration: the implosion of cavitation bubbles produces a specific noise. This manifests itself with the appearance of the first cavitation bubbles. The vibrations are felt due to the volume variation of the cavities and their uneven distribution in the channels impellers.
- Hydrodynamic effects: in areas where cavities appear, the regime of flow. The fluid containing the cavities will have a lower density which will influence it negative (decrease) pumping height, power absorbed, flow. The mixture density decreases in proportion to the increase in the concentration of cavitation bubbles which means that the degree of development of the cavity in the pump can be evaluated by influence on energy parameters.
- Cavitation destruction: the complex phenomena that accompany formation, the development and implosion of cavities on the solid surfaces of the impeller channel produce in time the local erosion of the solid material. This is due to the pulsating mechanical effects of the cavitation implosion produced on extremely small surfaces, which affect the internal structure of material. Over time, material dislocations occur and destruction spreads to larger and deeper areas. Material destruction also occurs due to chemical corrosion, electrochemical corrosion and mechanical corrosion, which appear in the phenomenon of implosion of the cavitation bubble.

It is necessary, therefore, to avoid the appearance of cavities, with all the phenomenon they have generate. The conditions of aspiration are those that determine the achievement of some minimum pressures on the impellers blades, equal to the vaporization pressure, which will leads to the appearance of the cavitation phenomenon in the pumps and even to its development.

2. THE CAD MODELS OF VOLUTE CASING AND IMPELLER

The NX Siemens CAD models for the hydraulic components of the pump were made based on the dimensions and geometry presented by some authors in their works [7].

The construction of the volute casing CAD model is focused on “Extrude” operations to make the inlet and outlet flanges. The difficult part of the model is that one containing the spiral (volute) casing area made by creating a “Helix” guide (orange curve in figure 3) along which the spiral contour of the casing through which the fluid will pass was drawn using the “Swept” option.

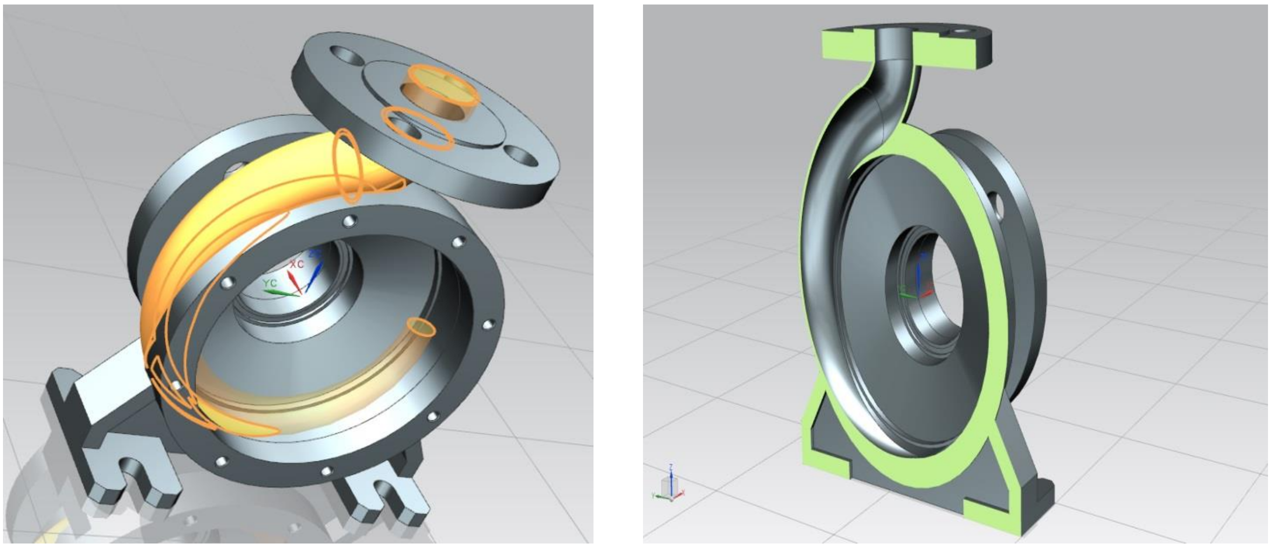

Fig. 3. Volute Casing with helix part and section viewing

The centrifugal pump designed in this work has a closed rotor (impeller) fixed directly on the shaft that transmits the angular velocity from the driven electrical engine. The impeller has a number of blades that will accelerate the liquid that will come in contact with them, the liquid being pushed towards (spiral) volute casing.

In the construction of CAD impeller model, the “Revolve” operation was used to rotate the sketches (figure 4).

To make the impeller blades, a profile blade sketch that was extruded was made. The other blades were made by multiplying the blade previously made using the “Pattern” (circular) operation (orange blade in figure 4). The two 3D models were assembled using "Concentric" and "Center" constraints (figure 5).

3. COMPUTATIONAL FLUID DYNAMIC (CFD) ANALYSIS

The NX CAD assembly is imported into the Design Modeler from Ansys CFX, the fluid domain is determined with the "Fill" option.
This domain has been divided into five subdomains. The transition from one subdomain to another is done through interfaces.

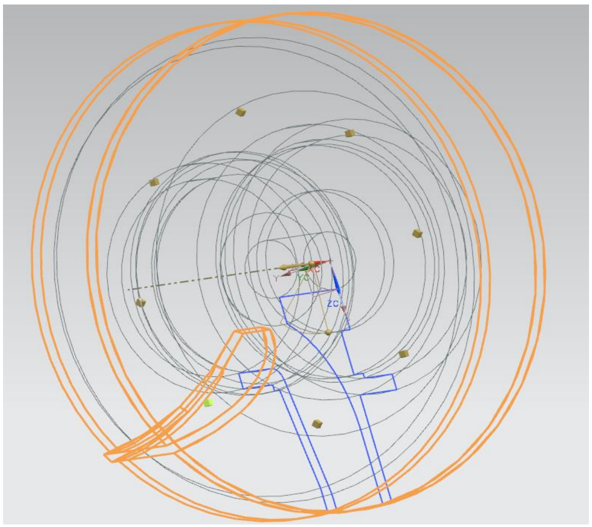

Fig. 4. "Revolve" of sketches (blue) and "Pattern" blade (orange) operation

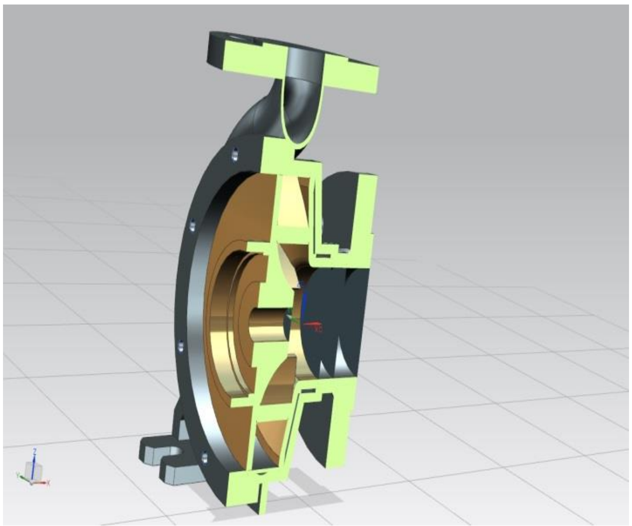

Fig. 5. Assembled NX CAD models (section viewing), volute casing and impeller

This was done because a subdomain of fluid will be rotated by the impeller blades and it is framed by other static subdomains thus creating a stratification of sandwich subdomains. This stratification helps a lot in applying the boundary conditions (figure 6).
Through the discretization operation with finite volumes, 53452 nodes and 189635 microvolumes were obtained (figure 7).

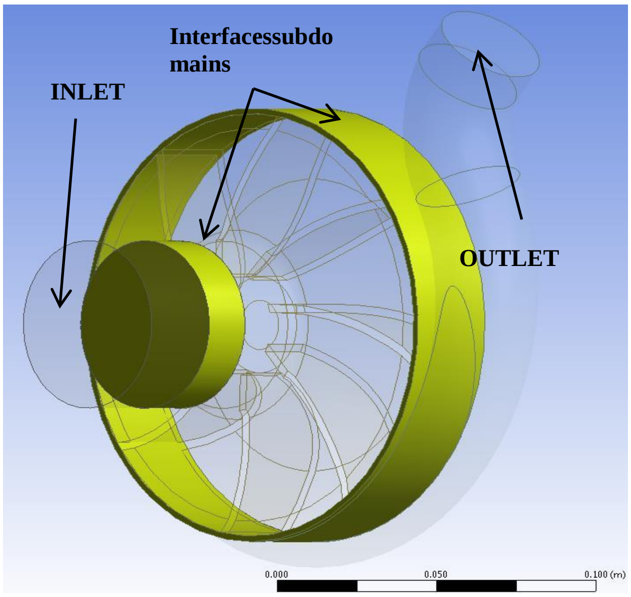

Fig. 6. Impeller subdomain (the rotating one) surrounded by two other static fluid subdomains

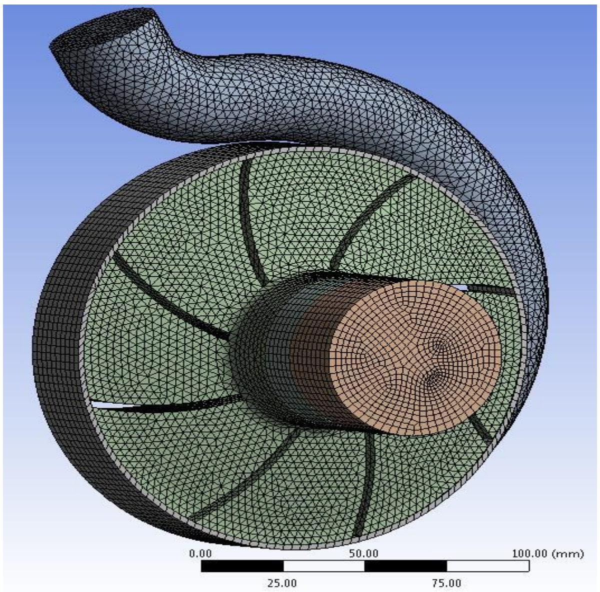

Fig. 7. Fluid subdomains volumes mesh

3.1. Boundary conditions

Water with 25°C its well-known properties and a vaporization pressure of 3170 Pa were used to model the flow. The speed of the inlet fluid was set at 3 m/s and this is in proportion to the "NPSH" (Net Positive Suction Head), notion used in the practice of pump operation. The boundary type condition for outlet was set "Opening", option "Entrainment" with relative pressure equal with 300000 Pa.
The cavitation model used is that of Reyleigh-Plesset one with the saturation pressure of 3170 Pa. The relative pressure of the model is set to zero.
When switching from one subdomain to another, boundary conditions of the interface type were used. When switching from a static subdomain to a rotating subdomain, the "Frozen Rotor" procedure was

applied. The same procedure was then used for the transition interface from the rotating subdomain to the static subdomain [8].It was considered that the impeller angular velocity is 2160 rad/s=20626.480 rpm considered in relation to an Ox axis, the value being taken with the minus sign because the direction of rotation is counterclockwise direction.
Wall boundary condition, option “No slip wall” were also used on the liquid surfaces that come in contact with the impeller blades as well as with the walls at the fluid inlet and the spiral part of volute casing.

4. RESULTS AND DISCUSSION

At the entrance to the pump the water has a speed of 3 m/s and is accelerated to a maximum speed at the blades near the outlet. Figure 8 shows that the maximum fluid velocity is at the end of the rotor blades towards the outlet more precisely in the entrance of volute spiral casing. Figures 9 show the absolute pressure field and the contour on the impeller blades.

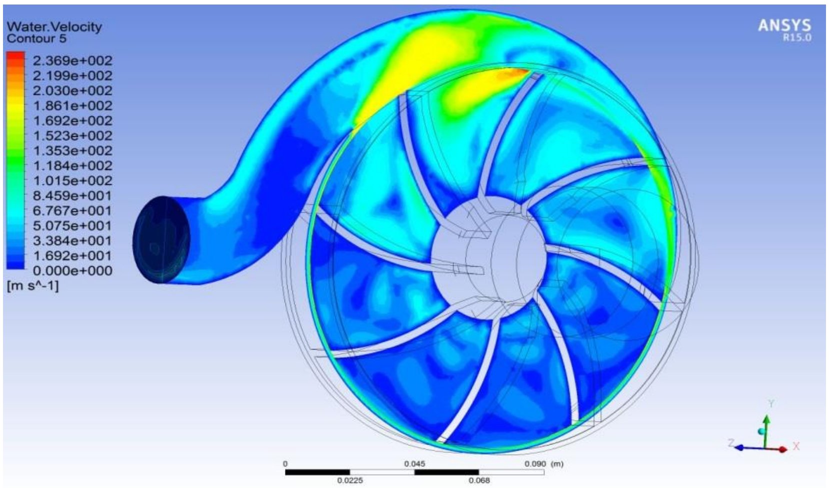

Fig. 8. Water velocity – orizontal section field

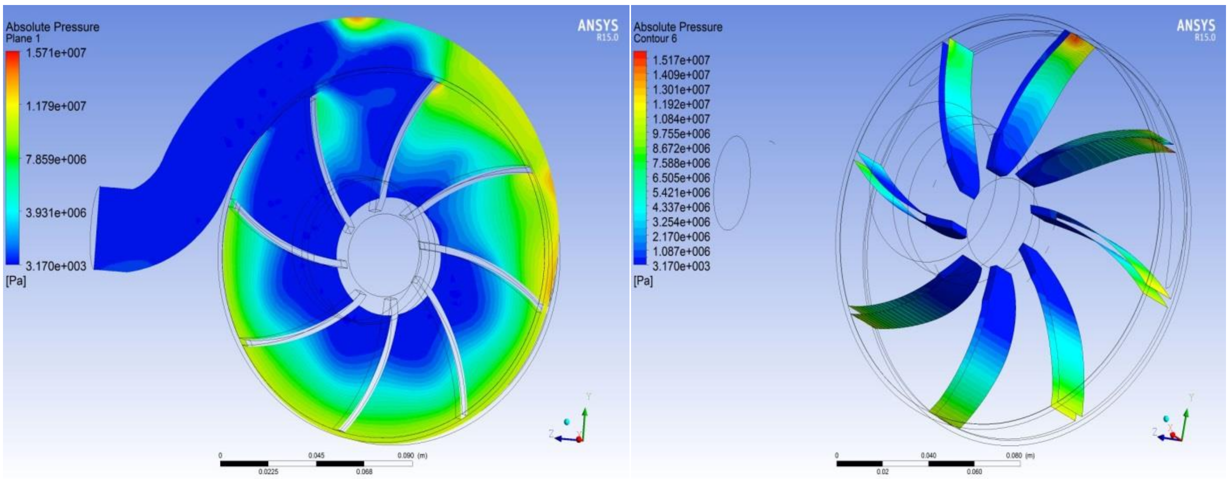

Fig. 9. Absolute pressure – horizontal section field and contours on blades

The lowest pressure is 3170 Pa which is the value of the vaporization pressure that was taken into account to model the cavitation phenomenon. If this phenomenon had not been taken into account, the model would have generated minimum negative pressure fields, which determined aspiration conditions. These low pressures of 3170 Pa (blue zones) are located in the vicinity of the blades at the inlet of the liquid in the pump, being areas susceptible to the formation and generation of the cavitation.
These blue areas are also observed on the faces of the impeller blades (figure 9), the cavitation phenomenon causing the blade material erosion and finally the rupture of the blades and the impeller failure.

5. CONCLUSIONS

In order to observe much clearer the regions with cavitation in the figure 10, the Vapour Volume Fraction was presented, the white areas being the areas where the vapours are developing.
The same presentation is 3D viewing, the isosurface

(figure 10) that delimits the volumes with vapours. From figure 10 it can be deduced that the white (maximum) areas of vapour volume fraction as well as the green areas with values over 0.5 vapour volume fraction can generate the cavitation phenomenon. In the article [8] the author demonstrated with Response Surface Optimization module of ANSYS that certain parameters can be varied in such a way that the generation of the cavitation phenomenon is restricted. Finally, increasing the pressure at the inlet of the liquid but also at the outlet and decreasing the impeller' angular velocity is the solution to have any centrifugal pump without cavitation.

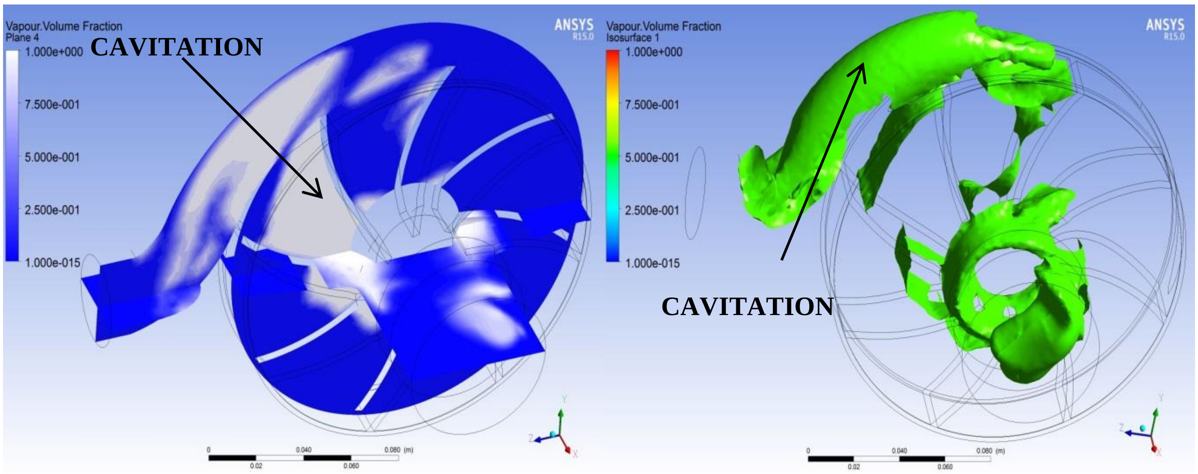

Fig. 10. Vapour Volume Fraction – horizontal and vertical section field and isosurfaces

For the ship' pumps, a major problem is that seawater is full of impurities that can form germs that promote cavitation. An important role is played by the filters from the sea chest, filters resistant to marine corrosion.

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