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Experimental study on developed air cavities under a horizontal flat plate.

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Experimental study on developed air cavities under a horizontal flat plate.

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SUMMARY

Developed air cavities can be used on the bottom of a ship for frictional drag reduction. An experimental study on the air cavity was carried out in a water tunnel. The cavity was created under a flat plate in the turbulent boundary layer (BL) behind a vertical cavitator.

A parameter study was performed in order to characterize the cavity under the flow conditions. Aspect ratio, pressure in the cavity, air losses and relevant scaling parameters were considered.

It was found that thin cavities become unstable due to relatively strong distortions of the free surface of the cavity. As a result, the maximum cavity length based on a Froude number criterion could not be reached.

INTRODUCTION

The frictional resistance makes up to some 70% of the total resistance of a cargo ship. It provides a great motivation to develop a technology of frictional drag reduction applicable to ships. It is known that the creation of artificially developed air cavities on the bottom of a ship can significantly reduce its drag [1, 2]. This is achieved by reducing the wetted surface on a horizontal part of the ship. One of the ways to create an air cavity under a horizontal surface is to inject air behind a cavitator. A cavitator is an obstruction mounted to the plate (or ship bottom) in span-wise direction that creates a suction pressure immediately downstream of it.

Numerous theoretical and experimental works have been done on drag reduction by air cavities. One of the first successful applications of this technology was reported from the Krylov Shipbuilding Research Institute in Russia in 1960th. Theoretical investigations of an artificially cavitating flow behind a wedge under a horizontal plate were supported by experiments. Nowadays, potential flow models to predict the behavior of the free surface are available [3]. However, there are still many questions open that need an answer before a wide practical application of this technology will be accepted. Real flow conditions, such as the presence of turbulence, require a deeper understanding of the free surface problem.

The influence of the turbulent boundary layer on the hydrodynamic characteristics of thin air cavities is one of the open issues. Related problems such as the required air flow rate for creation and maintaining of such a cavity, and the resulting drag reduction and required power for air supply (compressor power), are investigated experimentally and reported in this paper.

EXPERIMENTAL SET UP

Tunnel

In order to study air cavities under a horizontal plate a dedicated flow facility is required. The cavitation tunnel at Delft University of Technology was used as a base for conducting experiments for the current study (a description of the tunnel can be found in Foeth 2008). This tunnel was originally constructed to study cavitation on propellers and wings. For the purpose of friction drag studies with air ventilation, the cavitation tunnel was refurbished in order to house a new test section which allows for tests with air cavities. The old test section and the diffuser were redesigned and replaced for this purpose. The new test section is significantly longer than the old one which could be achieved by shortening the diffuser.

The new test section of the cavitation tunnel is a water channel with the rectangular cross-section (Figure 1). The length of the channel is 2130 mm. The parallel side walls and the bottom are made of Plexiglas plates of 35 mm. The cross-section at the entrance is 300*300 mm. The bottom of the test section is inclined in such a way that the cross-section at the end is 300*315 mm. This increase in depth of the measuring section is to compensate the boundary layer growth and to keep the center-line velocity constant (at least for a single phase (water) flow case). The maximum water velocity in the test section is 7 m/s. However, the maximum velocity at which the air injected into the measuring section does not recirculate is 3 to 3.5 m/s. The top wall of the channel consists of a horizontal test plate.

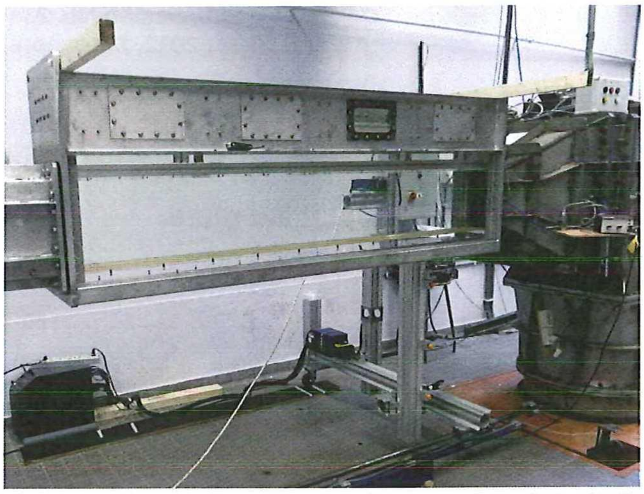

Figure 1: The new "Friction Drag" test section of the Delft Cavitation Tunnel with a traversing PIV set up underneath.

Plate and cavitator

The test plate is a replaceable 10 mm Plexiglas plate with an area of 2000*298 mm, which allows to have optical access also from the top. It is mounted to a frame of aluminum profiles. The frame can be ether firmly fixed to the test section or suspended by means of leaf-springs for the shear force measurement. There is a gap of 1 mm around the plate which is essential for the force measurement.

The air cavity was formed by injecting air behind a vertical plate with a sharp edge - a cavitator, protruding out of the test plate (Figure 2). The cavitator was located 50 mm from the leading edge of the test plate. The height of the cavitator was changed in the range of 0.5-2 mm. Two vertical plates of 30 mm height along the two sides of the plate prevent air escape from the cavity through the side gaps.

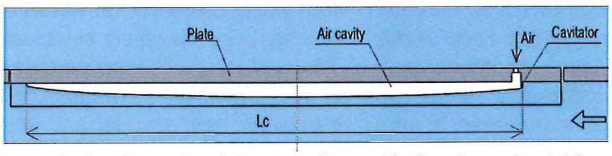

Figure 2: A schematic of the test plate with the air cavity (side view).

PIV

The water flow in the tunnel was characterized by planar Particle Image Velocimetry (PIV) with the field of view of 150*150 mm. For the boundary layer measurement the field of view was approximately 40*30 mm. Hollow glass spheres of 10 μm were used as tracer particles. A pulsed laser with optics were installed underneath of the test section. The camera and the laser with optics was placed on a traverse to be able to do measurements at any location in the channel.

The test section has good optical access from all four sides. It makes possible to visualize the air cavity from different directions. The cavity length and thickness were measured visually. Because the cavities were not completely 2-dimensional the following assumptions were done:

- the cavity length was defined as the one at the middle of the cavity;
- the cavity thickness was defined as the maximum thickness in span-wise direction.

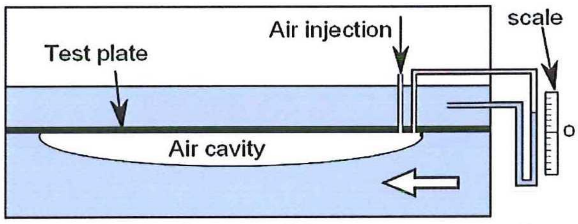

Figure 3: Principle of pressure difference measurement between the mean pressure in the cavity and the ambient pressure.

One of the governing dimensionless parameters for cavitation flows is the cavitation number:

$$\sigma = \frac{(p_\infty - p_{cav})}{\frac{1}{2}\rho V^2} \qquad (1)$$

In order to define it, the pressure difference between the mean pressure in the cavity and hydrostatic pressure at the plate level should be measured. A scheme of the measurement principle is shown in Figure 3.

Air from a central air supply was injected in the cavity by means of gas mass flow controllers. (Bronkhorst F-201CV and F-202A range up to 1 l/s).

RESULTS

The velocity profile at the leading edge of the test plate is shown in Figure 4 (top). The stream-wise velocity for this measurement was 2.68 m/s. As can be seen from the graph there are two distinguished velocity regions. The boundary layer region extends over 7.4 mm from the wall. The further velocity profile is uniform. A more detailed view of the BL is shown in Figure 4 (bottom). The distance from the wall (vertical axis) is normalized by the BL thickness. The velocity is normalized by the stream-wise velocity. The shape factor for the boundary layer is 1.38 which is close to the typical value of 1.3 for a turbulent BL [White 2006]. The profile of the BL is also in a good agreement with the $1/7^{th}$ power velocity profile in the BL . For all three measured velocities (1.5, 2 and 2.5 m/s) the BL at the beginning of the test plate was approximately 7mm.

A parameter study was performed in order to define the main characteristics of the cavity such as dimensions, pressure and air consumption. During these experiments the following parameters were varied: cavitator height h (0.5, 1, 1.5 and 2 mm), flow velocity V (between 1 and 3 m/s) and air flow rate Q (between 0.24 and 12 l/min). The cavity length L, the maximum cavity thickness H, and the relative pressure in the cavity were measured.

For each cavitator height the velocities varied in the mentioned range. For each velocity all the parameters were measured at different cavity length. The air flow rate was adjusted to obtain a certain cavity length.

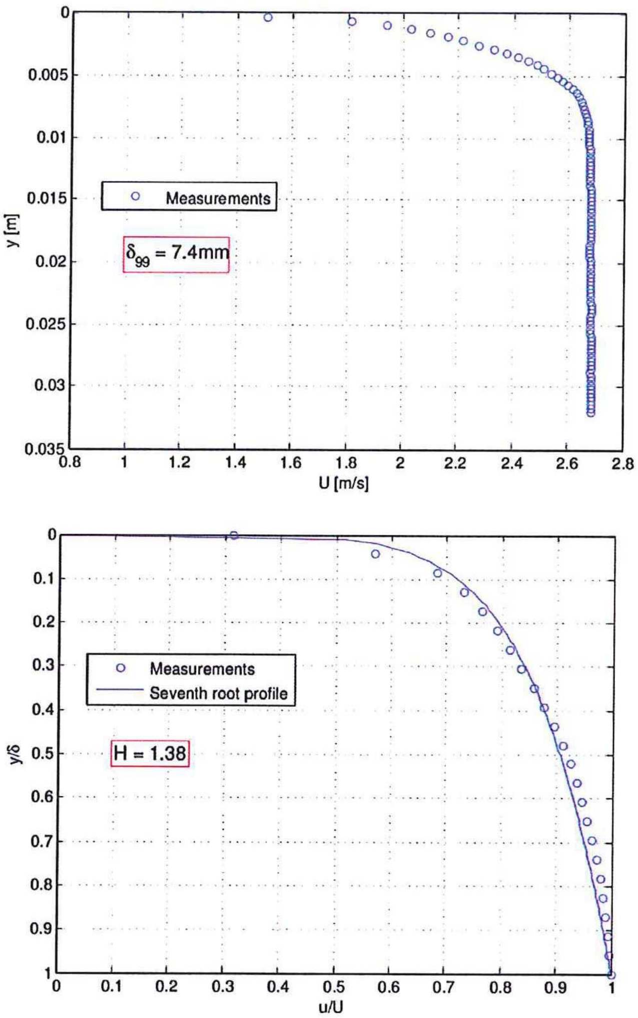

Figure 4: The velocity profile at the beginning of the test plate

It was observed that the maximum stable cavity length occurs at approximately a half of the gravity wave length λ, where the phase velocity of this gravity wave is corrected for the shallow water effect (Figure 5). And it does not depend on the cavitator height. Due to the limited length of the test section the maximum λ - limited cavity length could only be achieved at velocities lower than 1.7 m/s. The relation between a phase velocity and the length of the gravity wave is given as following:

$$V=\sqrt{\frac{g\lambda}{2\pi}\tanh\frac{2\pi D}{\lambda}} \qquad (2)$$

where D is a depth of the channel. For the deep water approximation the term $\tanh\frac{2\pi D}{\lambda}=1$.

For the case of relatively thin cavities another restriction plays a role. Secondary waves on the free surface of the cavity reach the surface of the plate and destroy the cavity. It leads to an unstable cavity length and high air losses. As a result, the maximum cavity length based on a half of the gravity wave length cannot be reached. This situation was observed for the smallest cavitator height of 0.5 mm.

The aspect ratio of the cavity *H/L* was defined for different *V*, *h* and *L*. The scaled aspect ratio of the cavity, as a function of dimensionless cavity length, $1/Fr = \frac{\sqrt{Lg}}{U}$ is shown in Figure 6.

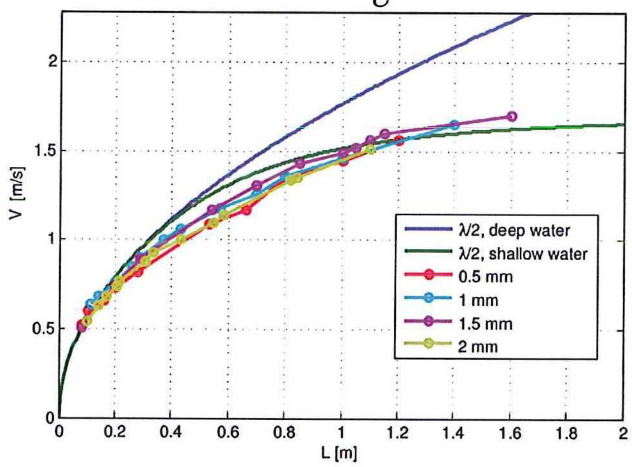

Figure 5: A phase velocity versus the length of a half gravity wave for deep (in blue) and shallow (in green) water approximations. Maximum cavity length for different *V* and *h* is shown by curves with circles.

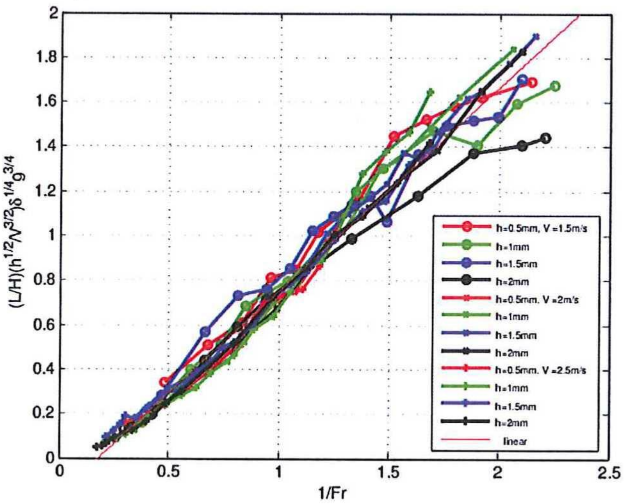

Figure 6: Scaled aspect ratio of the cavity as a function of 1/Fr.

Each curve represents measurements with constant *h* and *V* but various *L* by varying air flow rate. The curves show a similar linear relation between the normalized thickness-length ratio (*H/L*) for the cavity and the reciprocal value of the non-dimensional water velocity (1/Fr). The applied normalization of H/L appears to collapse all data into one linear relation. A physical rationale for this relation is however yet lacking.

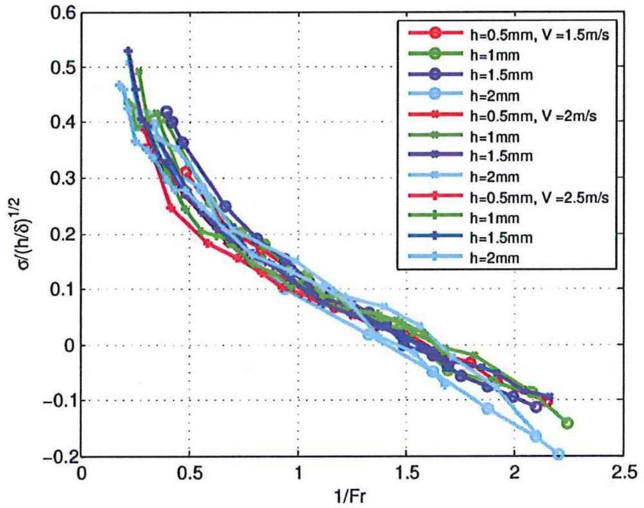

Figure 7: Scaled cavitation number versus 1/Fr.

The dependence of the scaled cavitation number σ on 1/Fr is shown in Figure 7. All the curves roughly collapse onto one curve.

As can be seen from the graph in Figure 6, all the cavities have a zero cavitation number at 1/Fr approximately 1.55. Longer cavities have a negative cavitation number implying that the pressure in the cavity is higher than the hydrostatic pressure at plate level. On the contrary, the cavity with a positive cavitation number has a lower pressure.

One of the important parameters for ventilated cavities is the air consumption by the cavity. It is known that air flux for creating the cavity is normally higher that the one to maintain it [6], [7]. The local air flux through the cavity closure region was defined for different cavity lengths. A typical measurement result of such a measurement is shown in Figure 8. The vertical axis shows the air flux and the horizontal axis the cavity length. The cavitator height was 1.5 mm and the velocity was 1.7 m/s. From the graph we can see that, indeed, the maximum air consumption is when the cavity is short. Then it goes down with the cavity length increasing and reaches it's minimum at maximum stable cavity length. The irregular behaviour of the air consumption at the intermediate part is most likely related to the wave pattern on the cavity surface. As was observed, two main factors cause air leakage from the cavity closure region: the first one is the re-entrant jet which is a typical phenomenon for developed sheet cavitation; the second is the wave pattern at the free surface. Each of these mechanisms contributes differently depending on flow conditions and geometry of the cavity. For the present study the contribution of the re-entrant jet was the biggest for relatively short cavities, whereas waves on the free surface cause significant air losses for long cavities.

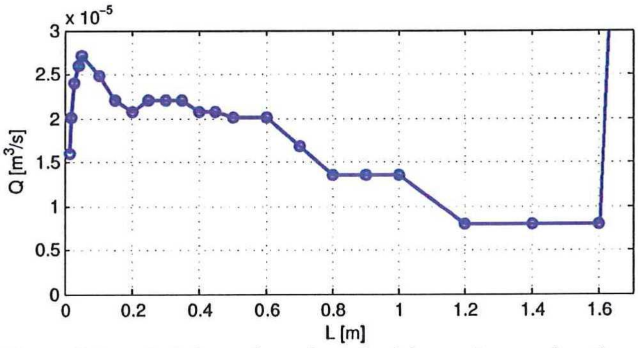

Figure 8: Local air loses from the tail of the cavity as a function of it's length.

A typical air cavity surface can be seen in Figure 9. In this case the free surface waves are relatively small compared to the cavity thickness. Two types of waves on the free surface can be distinguished. The first one is caused by turbulent fluctuations in the water at the interface. The second one is caused by reflections of diverging waves from the side walls. Capillary waves are also present on the interface but don't play a significant role either on the cavity geometry or air consumption because of their small size.

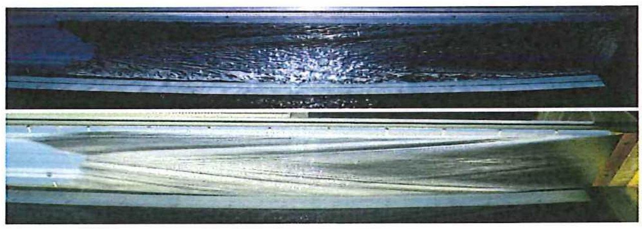
Figure 9: Air cavity under the plate. a) – instantaneous wave profile (short exposure time) b) – averaged wave profile (long exposure time). Flow from right to left. h=1mm, V=1.5m/s.

The minimum air flux required to form the cavity was found for four cavitator heights at different velocities. The results of these measurements are presented in Figure 10. The air flux on the vertical axis is made non-dimensional with the velocity, cavitator height and width b. The velocity on the horizontal axis is the velocity at the cavitator edge height. It was found by assuming the 1/7th power velocity profile in the BL. Again, all the data collapse on a straight line. From the experimental data, it can be seen that thin cavities consume less air if they are stable.

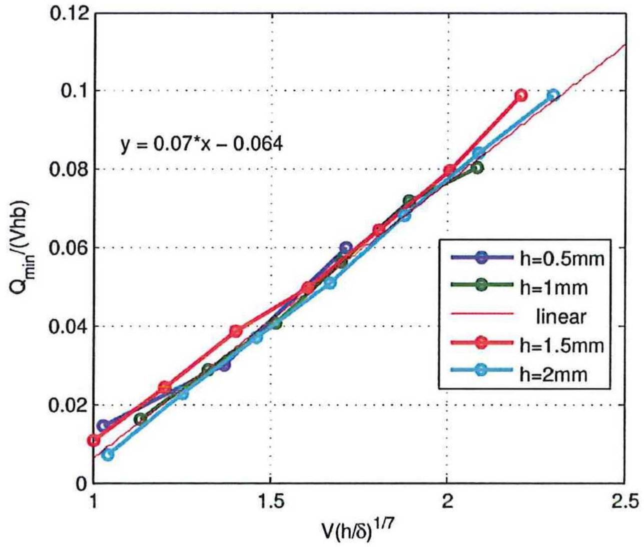

Figure 10: Dependence of the dimensionless air flux on the velocity at the cavitator edge.

CONCLUSION

A developed air cavity originating from a cavitator mounted underneath a horizontal flat plate was studied experimentally in a water tunnel. The cavity was created by injecting air behind a cavitator. The experimental data allowed us to make a correlation between the main parameters of the flow. A dependence of the scaled aspect ratio of the cavity and the cavitation number on the dimensionless length of the cavity was shown. All the tested cavities had a zero cavitation number at $1/Fr \approx 1.55$. The longer cavities had a negative cavitation number, hence a positive pressure in the cavity.

Two mechanisms which cause the air losses from the cavity were defined. The first mechanism is governed by the presence of the re-entrant jet, continuously shedding bits of the air cavity in the closure region. The second mechanism is caused by waves on the free surface. The contribution of each of these mechanisms depends on the flow conditions (flow velocity, turbulence intensity) and geometry of the cavity.

Furthermore, if the roughness of the free surface is high compared to the cavity thickness, the cavity break up. In that case, the maximum cavity length based on the transverse wave length cannot be reached.

ACKNOWLEDGMENTS

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