Experimental evidence of nucleation from wall-bounded nuclei in a laminar flow

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Abstract. The importance of nucleation from wall-bounded nuclei for cavitation and especially cavitation inception is undisputed. Although various theories and models found their way to standard literature, there is a lack of experiments allowing a closer look onto the process of nucleation. In the present paper we present a new experimental set-up that allows the investigation and analysis of nucleation from wall-bounded nuclei. The experimental findings support an extended understanding of nucleation as a self excited cyclic process. Impressive high-speed visualisations can be found in the supplementary material.

1. Introduction
Investigations about the role of nuclei and nucleation for the inception and formation of cavitation are part of cavitation research since Harvey postulated the existence of gas filled crevices on surfaces and particles in liquids [1]. In a supersaturated solution these wall-bounded nuclei can produce free nuclei due to mass transfer of gas or themselves work as weak-spots in the liquid that are necessary for the occurrence of a phase change under technically relevant pressures. The former process is referred to as nucleation and is examined in this work. In case of hydrophobic surfaces the wall-bounded nuclei are stabilised by the effect of surface tension that lowers the pressure in the gas pocket below the pressure of the surrounding liquid and thus impedes diffusion of gas out of the crevice, unless the liquid is undersaturated [2]. In the recent decades many important works on this subject have been published. Mørch gives an extensive overview of investigations about cavitation nuclei both theoretical and experimental ones [3][4]. The review article of Jones et. al [5] focuses on nucleation from wall-bounded nuclei.

The present paper shows new experimental results gained in a benchmark experiment that has been suggested by Peters et al. [6]. Furthermore we provide new insights into the mechanism of nucleation. A laminar radial gap flow is used to observe nucleation at artificial nucleation sites and allows to investigate the physics of nuclei production. Since the experimental set-up is reduced to the essentials we can easily control the flow parameters and also benefit from the optical accessibility to generate reproducible data. The paper can be outlined as follows. In section 2 we explain the experimental set-up shortly and describe the governing equations. In section 3 we show first experimental results. Section 4 closes the article with a conclusion.

2. Experimental set-up and governing equations
Experiments on cavitation are often carried out in complex test facilities since the results are to be applied on likewise complex machines such as pumps, propellers or valves. Due
to the complexity and size of these test facilities (e.g. cavitation tunnels) there is often a limited accessibility to the working section resulting in extensive experimental procedures and time-consuming conversion work. Without a doubt studies of small-scale phenomena such as nucleation are difficult to study in such experimental set-ups. The experimental set-up we use for our nucleation experiments is kept simple so that a good accessibility (mechanical and optical) is ensured and we can easily control the experimental parameters.

Inside of a cylindrical vessel a laminar radial gap flow is realised, see figure 1. The gap is formed by spacers which are attached at three points between a steel plate and a glass plate with radius $R_1$. The half gap height $h$ can be adjusted between 0.05 and 1 mm. Blind holes with a depth of less than 1 mm and different diameters $D$ (0.2, 0.4, 0.6, and 0.8 mm) on different radii $r$ (10, 15, 20, 30, and 40 mm) drilled in replaceable steel plates serve as artificial nucleation spots which we observe in our experiments. The glass plate allows the use of high-speed imaging. The flow is driven by a speed-controlled gear pump that is connected to a bore (radius $R_2$) in the centre of the steel plate. A tank is used as a reservoir and decelerates the flow so that bubbles can rise to the surface. The liquid flows back to the vessel making a closed loop. We measure the pressure in the bore and the volume flux with an ultrasonic flow meter that is non-sensitive to small amounts of free gas. In addition, we measure the temperature and the oxygen content of the liquid in the vessel. Before starting the experiment the blind holes are filled with air by a syringe. It is ensured that the liquid is at least saturated at ambient pressure. Otherwise the gas in the crevices would dissolve in the surrounding liquid. The liquid we use is a silicone oil with a density of 960 kg/m$^3$ and a kinematic viscosity of 100 mm$^2$/s at 25°C. The Bunsen coefficient is 0.168 at 25°C and 1 bar [6]. For the high-speed visualisation we use an IDT Motion Pro Y7 S3 camera with a resolution of 1920 x 1080 pixels and a maximum frame rate of 10600 frames per second. The frame rate can be increased by reducing the resolution. We measure the nucleation rate by means of image processing.

Figure 2 shows the principle of the nucleation process that includes the recurring grows and detachment of gas bubbles from wall-bounded nuclei we introduce here. It is a self excited cyclic process triggered by the bubble detachment. According to the convection-diffusion characteristics of the nucleation process the mass flux of gas that diffuses into a nucleus depends on both the supersaturation of the liquid and the fluid velocity. The critical size corresponding to

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**Figure 1.** Test section of experimental set-up. Laminar radial flow between two closely spaced parallel plates with a sink at the centre. We consider the inflow case. Blind holes in the steel plate work as wall-bounded nuclei.
the detachment depends on the velocity and the wall shear stress. In the present experiment the
supersaturation occurs because of a pressure decrease along the flow path in inward direction.
Following a flow perturbation theory, Savage [7] derives an approximate solution of the Navier-
Stokes equation for a laminar-radial gap flow that allows the calculation of the local pressure
\[ p(r) - p_1 = \frac{3\mu Q}{4\pi h^3} - \ln \left( \frac{R_1}{r} \right) + \mathcal{O}\left( \frac{R_1^2}{r^2} \right) + ... \]

with an outer radius \( R_1 \) and a corresponding pressures \( p_1 \) and the dynamic viscosity of the
liquid \( \mu \). This approximation is only valid for small Reynolds numbers. The volume flux is
set to be positive for the inflow case. The concentration \( c \) of gas dissolved in a liquid in an
equilibrium is given by Henry’s law [8] \( c(r) = p(r)k_H \) where \( k_H \) is denoted as Henry constant.
Assuming that the liquid in the vessel is saturated with gas in equilibrium at the inlet \( c_1 = p_1k_H \),
the liquid becomes supersaturated due to the pressure decrease in inward direction. The local
supersaturation \( \chi(r) = c_1/c(r) \) can be specified with the equation above and Henry’s law.
Equation (2) shows that it is necessary to use a liquid with a relatively large viscosity to achieve
relevant supersaturations. Otherwise, the gap would have to be very small. The area-averaged
velocity \( u(r) = Q/(4\pi rh) \) can be calculated with the continuity equation. Using the velocity
profile derived by Savage [7] one eventually gets the wall shear stress as \( \tau(r) = 3Q\mu/(4\pi rh^2) \).

3. Experimental results
As already mentioned the three independent parameters including supersaturation, fluid velocity,
and wall shear stress influence the nucleation process and in particular the nucleation rate.
In Figure 3 the nucleation rate is plotted versus the local flow velocity for different gap
heights and different supersaturation. The nucleation rate increases with increasing velocity
and supersaturation. The exact influence of the parameters remains hidden since the gap height
also influences the nucleation rate. In future experiments the gap height has to be increased to
suppress this influence. Figure 3 also demonstrates that nucleation rates over several orders of
magnitude are achievable. Up to now the largest nucleation rate we measured is 1000 Hz which
is of the order of nucleation rates observed in real cavitating flows [9].

Figure 4 shows the growth and detachment of a gas bubble from a wall-bounded nucleus.
The process works as follows. A small part of the nucleus extends beyond the edge of the bore
in the direction of the flow (Fig. 4 a-c). In a short amount of time a larger bubble is formed
(Fig. 4 d) which is still connected to the wall-bounded nucleus. The bubble finally detaches due
to the acting forces and is carried away with the liquid flow (Figs. 4 e-f). A high-speed video of
the process can be found in the supplementary material.
Figure 3. Nucleation rate depending on velocity, supersaturation and gap height \((D = 0.6 \text{ mm})\). Different symbols mark different gap heights. The solid lines indicate constant supersaturation.

Figure 4. Growth and detachment of a gas bubble from an artificial wall-bounded nucleus \((D = 0.8 \text{ mm})\). The time interval between the images is 1 ms. The nucleation rate is 10.2 Hz. Flow direction is from left to right.

4. Conclusion
Although there is no doubt about the relevance of nuclei and nucleation for cavitation and cavitation inception, there are many unanswered questions. To gain new insights into the physics of nucleation we use a novel experimental set-up that allows the investigation of nucleation. The following list summarises the results and gives suggestions for future works.

- The nucleation rates depend on the level of supersaturation, flow velocity and wall shear stress.
- The nucleation rates are remarkably constant over time and show only small fluctuations.
- Observation of nucleation rates from 0.1 up to 1000 Hz are possible.
- In the present experiment the nucleation process depends on the length ratio \(h/D\). In order to make a better correspondence to technical flows this ratio has to be increased.
- It is also necessary to investigate smaller bore diameters. Diameters in the size range of 1 \(\mu\text{m}\) to 10 \(\mu\text{m}\) are relevant for this issue.
- Due to the simplicity of the experiment, it can also be used as a benchmark for numerical simulations.

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References
[1] Harvey E, Barnes D, McElroy W, Whiteley A, Pease D and Cooper K 1944 \textit{J. Cell. Physiol.} \textbf{24} 1–22
[2] Atchley A and Prosperetti A 1989 \textit{J. Acoust. Soc. Am.} \textbf{86} 1065–1084
[3] March K 2007 \textit{Phys. Fluids} \textbf{19}
[4] March K 2008 \textit{J. Hydrodyn.} \textbf{21} 176–189
[5] Jones S, Evans G and Galvin K 1999 \textit{Adv. Colloid Interface Sci.} \textbf{80} 27–50
[6] Peters F and Honza R 2014 \textit{Exp. Fluids} \textbf{55} 1786
[7] Savage S 1964 \textit{J. Appl. Mech.} \textbf{31} 594–596
[8] Henry W 1803 \textit{Philos. Trans. R. Soc. London} \textbf{93} 29–274 ISSN 0261-0523
[9] Guennoun F, Farhat M, Bouziad Y A and Avellan F 2003 \textit{CAV 2003: Fifth International Symposium on Cavitation}