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Mitigation of cavitation effects by means of gas bubbles on a surface

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Abstract

Cavitation turned out to be a severe problem for the pulsed spallation neutron sources which are currently under construction in the US and in Japan. Target windows are eroded quickly and are still far from meeting their preferred lifetime requirements. A simple idea is proposed how to protect the window surface: with a sufficient number of tiny bubbles of some non-condensable gas sitting at the surface. The suggested procedure aims at protecting almost any surface prone to cavitation attack by ensuring a sufficient density of gas bubbles of suitable composition and size residing right at the surface to be protected and its close vicinity. The amount of gas can be controlled accurately to yield an advantageous volume fraction of gas in the liquid in the relevant volume. In order to concentrate gas at an exposed surface it is proposed to structure it in a suitable way to agglomerate, trap and retain gas bubbles there. A fraction of the bubbles is allowed to escape to the volume of the liquid exerting well established beneficial effects there. Lost gas can best be replenished through feeding ducts inside the wall structure. In the following a short outline of proposed implementations and expected effects is given.

1. Introduction

The trigger for the present work stems from the occurrence of unexpected problems with cavitation at pulsed neutron sources, which turn out to be the limiting factor for the lifetime of beam windows [1–3]. Beyond the rather peculiar incidence at mercury targets in spallation sources, cavitation is an almost ubiquitous phenomenon occurring in a vast range of machinery involving liquids – amongst others in diesel engines, pumps, turbines, water ducts, and ship propellers [4].

Cavitation occurs when vapor bubbles in a liquid implode violently. This leads to the severe degradation of surfaces exposed to the liquid when the vapor bubbles collapse at the interface. Common ways to mitigate the ensuing erosion include optimizing geometrical shape, hardening surfaces and adding gas to the bulk of the liquid.

In a recent comprehensive treatise three different and probably co-occurring damaging mechanisms leading to cavitation erosion have been listed: re-entrant jets, vortices and shock waves [5]. Vapor bubbles arise preferentially at some inhomogenities, i.e. seeds. Despite much progress, their growth and collapse phases still appear to be not yet completely understood [6]. Two distinct phases of the damaging process can be discerned: an incubation phase where

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isolated pits are observed and a later erosion phase with overall surface attack and substantial mass loss [3,7].

2. Pitting in spallation sources

Cavitation erosion on beam windows in spallation sources is attributed to the immediate shock wave stemming from the pulsed heat deposition by the proton beam in the Mercury target volume [1–3,8].

The design of the European Spallation Source ESS foresaw the dispersing of helium bubbles in the bulk of the Mercury to dampen shockwaves stemming from the power deposition by the pulsed proton beam [1].

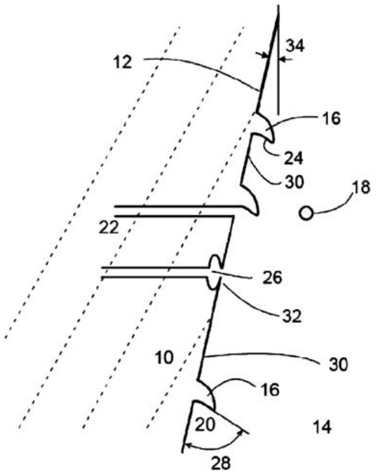
The American and Japanese pulsed spallation sources SNS (Spallation Neutron Source) and JSNS (Japanese Spallation Neutron Source), respectively, face the same problems, and work on the issue is advanced in a joint effort [9–11]. The best way to protect beam windows found so far is to apply a special surface conditioning, i.e. 'Kolsterizing', which is a low temperature carburization treatment [2]. The such hardened surface exhibits a much prolonged incubation phase, but once severe erosion starts, degradation is considerably faster than for untreated 316 SS material; fatigue leads in the end to about the same rather short lifetime of the beam window [10].

According to expectations, gas added to the bulk of the mercury promises to independently extend the window life time [9]. Experiments, which will be performed mid 2005, will thus focus on mitigation by adding gas bubbles to the liquid metal [9]. There have been indications for a protective effect of a more or less continuous gas wall separating the liquid from the container surface, which have not been pursued or exploited yet [11].

3. Mitigation of cavitation effects by means of gas bubbles on a surface

The idea advanced here is to protect a surface against cavitation damage by covering it with many bubbles of a sufficiently non-condensable gas. Surface structuring provides anchor points and traps making bubbles reside at the surface. Bubbles are best expelled from pores in the surface which is to be protected. Some fraction of these bubbles is allowed to escape and gas lost to the liquid is replenished.

As depicted in Fig 1, a wall (10) with a surface (12) is facing a liquid (14). The wall in total might be inclined from the vertical by an angle (34) so as to enhance the capturing of gas bubbles from the liquid. The surface is structured in a special way with some types of protrusions (16) arranged so as to catch gas bubbles (18) moving with the flow of the liquid or rising within the liquid due to their buoyancy. The recessions (20) of the surface thus defined by the protrusions (16) provide the preferred positions and anchoring spots for gas bubbles. In case active gas replenishment is incorporated, gas is fed through thin ducts (22) to the rear wall of such gas pockets (24). In addition or in place of the extensions, imperfections and irregularities in or on the wall (10) may be introduced. Such may cover all or part of the wall depending upon application. In another embodi-



LIST OF ELEMENTS

10	structure, solid / liquid interface
12	surface
14	liquid
16	protrusion, extension, "lip"
18	gas bubble
20	recess
22	gas feeding duct
24	gas pocket
26	cavity
28	angle protrusion / general surface
30	smooth section
32	bleeding hole / outlet
34	angle of inclination against vertical

Fig. 1. Sketch of surface with protrusions and gas replenishment.

ment with gas replenishment the surface might be essentially flat with distributed gas bleeding holes (32). Gas bleeding holes (32) are openings from which gas escapes in a steady flow or in a controlled and regulated, even pulsed, manner. According to the specific requirements of the exact locations, geometrical implementation, size and diameter of optimum bleeding holes might differ in detail.

To protect beam windows in spallation sources an optimum size for gas bubbles of about 10–100 μm has been found [8]. Helium bubbles of this size can be expelled from bleeding holes of similar diameter. Given the intermittent occurrence of the load it might be best to also supply the gas in a pulsed manner. Synchronized at a suitable phase to the beam pulses a gas pressure wave in the feeding ducts can produce the right amount of gas blowing up to bubbles or expelled just at the appropriate moment.

In an extreme case the gas could be fed such as to cover the wall completely with a closed sheet during the short time spans when the pressure wave in the Mercury is about to hit the wall. The gas layer thus insulates the wall exactly when it is required; the jump in impedance stops the pressure from even arriving at the solid wall structure. The wall would be insulated only when really necessary – in total only a small fraction of the time. Thus cooling of the wall with the flowing Mercury probably would not be hampered considerably.

Assuming a hardened surface which can stand a few bubbles imploding, i.e. with a reassuringly long incubation phase, the gas feeing can be actively controlled via feedback derived from noise measurement on the wall.

Admittedly, the simple adding of gas bubbles entrained to the liquid metal flow at a more remote and accessible point in the Mercury loop round a spallation target would be preferred, but there appear to be advantages of supplying the gas directly at the window.

4. Eight ways how tiny bubbles could protect a surface

In the following sketch different effects and modes of actions are briefly enlisted, which are proposed for detailed investigations.

(1) Especially at the surface, bubbles dampen the impact of pressure waves in the liquid caused by energy deposition and by the implosion of bubbles and their rebounding due to cavitation in the main liquid volume.
(2) Bubbles collapse asymmetrically; contrary to a rigid wall a gas-clad one should not ‘attract’ micro-jets.
(3) Collapsing bubbles move preferably away from a free surface, i.e. towards a wall; with enough gas at the surface a wall might look rather like a free boundary.
(4) During the growth phase of a bubble the above effect works similarly in principle, i.e. bubbles will be repelled from a rather hard wall; this does not necessarily contradict or conflict with point (3), in a pulsed operational regime (3) and (4) can refer to different points in the cycle.
(5) Developing vortexes will tear bubbles away from the wall rather than collapsing there and ripping out material from the substrate.
(6) Bubbles, which escape from the wall, contain non-condensable gas; if they form the nucleation points for true cavitation bubbles in the volume of the liquid their collapse and rebounding is damped, ‘cushioned’ due to their non-condensable content fraction.
(7) Many cavitating bubbles from many nuclei lead to a dilution effect, i.e. each single one implodes less violently; many bubbles disperse the energy and reduce pressure waves at their origin.
(8) Escaped bubbles attenuate the propagation of pressure waves in the volume of the liquid.

Furthermore:

(1) If enough bubbles dwell on a wall, this reduces the friction of the liquid moving along that surface, i.e. drag.
(2) The admixture of gas bubbles allows for some adjusting of the viscosity of the liquid in the effected volume.

5. Wider applications

If gas bubbles right at a surface prove to be an efficient means to protect the interface from cavitation erosion as predicted and as will be clear in the near future from the experiments performed for the spallation sources, this ought to apply to a very broad range of applications. Any machinery working with liquids where certain parts and surface patches are susceptible to pitting damage would be a good candidate for surface protection by means of gas bubbles, sufficiently non-condensing, sitting right at the interface and escaping to the boundary layer in the liquid. Active control of the gas feeding would allow continuously optimizing the characteristics of a device in a liquid, e.g. to tune and improve the performance of a ship propeller in the water.

Venting sufficient quantities of gas directly through the to be protected surface looks like a task which can be met with up to date production technology. As developed for gas bearings, laser drilling would offer a way to produce very many small-diameter holes in a surface [12]. Probably, a laser drilling operation can be combined with a surface treatment step for hardening.

Assuming a wide potential applicability of such surface structuring mitigating cavitation erosion, Paul Scherrer Institut (PSI) has recently filed a corresponding patent application [13].

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