SHIP DRAG REDUCTION BY HULL VENTILATION FROM LAVAL TO NEAR FUTURE: CHALLENGES AND SUCCESSES

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SOMMAIRE

La réduction de la trainée par ventilation de carènes est une technologie efficace et protectrice pour l’environnement. Récemment, l’intérêt pour la réduction de la résistance par cavitation à des petits nombres de Froude s’est manifesté en Europe : quelques essais sur modèles ont été réalisés, mais aucun essai de bateaux à l’échelle un n’a été publié. Cependant, 4 types de bateaux de rivière et de barges avec des cavités sur le fond de leurs carènes ont été expérimentés avec succès en URSS de 1966 a 1989. Nous présentons ici les résultats les plus importants en expliquant les mécanismes hydrodynamiques en jeu et en donnant des comparaisons des résultats Russes et des essais sur modèles récemment obtenus aux USA. Un brève note sur la réduction de la résistance des bateaux par microbulles est également donnée.

SUMMARY

Drag reduction by hull ventilation is an effective and environmentally friendly technology. Recently an interest to drag reduction by cavitation at small Froude numbers has appeared in Europe, where some model tests have been performed with no results of full-scale experiments yet. However, 4 types of river ships and barges with bottom cavities were successfully tested in Soviet Union from 1966 till 1989. The most substantial information on them is presented here with explanation of hydrodynamic fundamentals and comparison of the Russian data with model test trends recently obtained in USA. A brief note on microbubbles drag reduction for ship forms is also provided.

1. INTRODUCTIONS

Reduction of ship drag is an eternal problem because the drag reduction lowers the fuel consumption and, as a result, moderates prices of cargo delivery or other services provided by ships. The annual world fuel consumption by 96 thousand sea commercial ships exceeds 250 million tons in 2007. Dozens of thousand inland ships and tugs significantly add to it. The long-term trend of the fuel cost is the cost forestalling rise relatively to other shipping expenses. This trend amplifies the importance of the problem, as well as the modern restrictions on carbon dioxide emission do. Of course, there is no the single best drag reduction (DR) technology for all ships, with variety of their dimensions and speeds.

Ventilation may lead either to a friction reduction due to reduction of the fluid density in the hull boundary layer and increase of its thickness, as microbubble drag reduction (**MDR)** does, or to a reduction of the hull wetted surface due to displacement of the boundary layer from the hull by an air layer, as drag reduction by bottom cavitation (**DRBC**) does. The last method (first claimed by Laval in his 1883 patent) is aimed on the direct use of the small density of the air that is around 1/800 of the water density. The local hull friction decreases proportionally to the density of the layer contacting the ship hull.

Diverse devices for practical invention of this idea were claimed in many patents (in USA, from submitted by Owen in 1885 to submitted by Lang in 2002). These patents, however, did not result into a DR technology because the claimed design was either intuitive or based on the data related to missile cavitation and corresponded to flows at very high Fr. The fate of such designs was impressively generalized by Foeth [1] who wrote that "*the application of air cavities to any hull form without consideration and understanding of the local dynamics of the flow can have counterproductive results*".

On the other hand, it was not well known that even Russian engineers with their outstanding results on DRBC started with an unsuccessful attempt: In 1957, a river barge of 1800 tons was supplemented by keels with a sloped plate clamped as a cavitator between them and compressed air was supplied to the bottom. The first full-scale test gave a 5% drag reduction, but the repeated test gave 0%.

Indeed, it is not trivial to create and maintain a stable air layer on the ship hull with relatively small energy losses on air supply. However, hydrodynamics already found how to do it.

2. FUNDAMENTALS OF DRAG REDUCTION BY VENTILATED CAVITATION

The studies of cavitation historically started from propeller vapor cavitation, whereas ventilated cavitation was first studied for enhancement of missiles. These cavitating flows have formed the conception of cavitation in the minds of the majority of engineers. However, such flows at high Froude number $Fr = U/\sqrt{gL}$ undergo insignificant buoyancy impacts. Indeed, shapes of large cavities (much larger than the boundary layer thickness) depend on interaction of the water inertia lengthening cavities, the water pressure compressing them and the gas buoyancy deflecting up their tails. So, the flow governing parameters are ratios of these mentioned forces: cavitation number $\sigma = 2(P_\infty - P_C)/\rho U^2$ and Fr^2. The second ratio has a little impact on the cavity at $Fr>>1$, but for $Fr<<1$, it is the major parameter because the cavity vertical deflection is proportional to Fr^{-2}, whereas σ becomes a secondary parameter. Further, there is a pulsating cavity tail and a cavitation-induced drag penalty caused by the tail pulsation, whereas the hull surface covered by the cavity is free of the water friction. DR by partial cavitation is possible because under certain conditions, partial cavities exist without a drag penalty. An illustration of this (after Kopriva at al [2]) is shown in Fig.1. For a design pair $\{Fr, \sigma\}$, the drag penalty is zero, the total drag has a minimum.

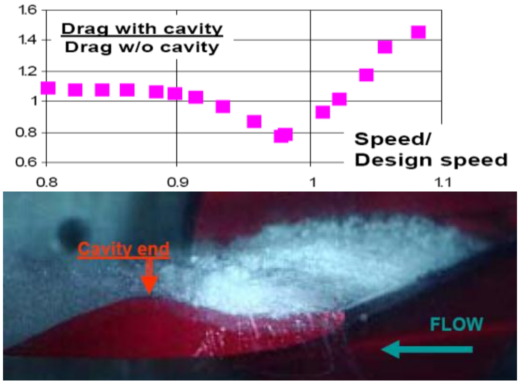


Figure 1 Typical measured drag reduction speed range for partial cavitation (top) and stable cavities over a hydrofoil(bottom).

The first success in ship DR by partial cavitation was achieved on the basis of the Butuzov's [3] theoretical analysis. Because only cavities of a small thickness to length ratio represent a practical interest (as shown in Fig. 2), linear theory analyzing small induced velocities was used by him.

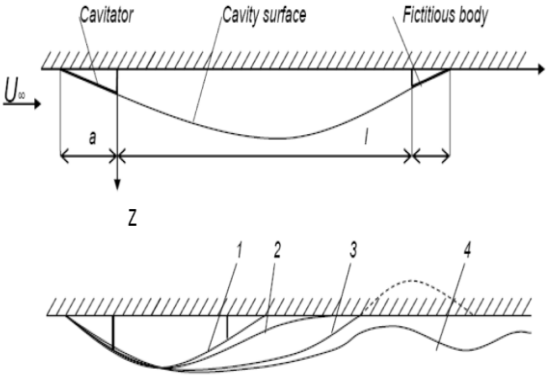


Figure 2 Scheme of 2D cavitating flow under the flat plate (top; the fictitious body length is *b*) and computed cavities of various lengths (bottom; 1 - a cavity with drag penalty proportional to the fictitious wedge size; 2 - a cavity with smooth penalty-free attachment to the plate; 3 -a numerical solution for unstable cavities; 4 - an infinite wavy cavity).

These velocities were computed using sources distributed along the plate itself, with the source intensity *q* expresses through ordinates of the cavitator, cavity and fictitious body by the formula $q(x) = 2U_\infty dz/dx$. Them the pressure constancy condition for a cavity is

$$\frac{1}{Fn^2}\int_0^x \frac{dz}{d\xi}d\xi + \frac{1}{\pi}\int_0^1 \frac{dz}{d\xi}\frac{d\xi}{(\xi - x)} + \frac{\sigma}{2}$$
$$= \frac{\alpha}{\pi}\,\ell n\left|\frac{a+x}{x}\right| - \frac{\beta}{\pi}\,\ell n\left|\frac{1-x}{1+b-x}\right| \tag{1}$$

Here z(0)/a=-α, all lengths are normalized by a given cavity length L_C, the wedge length *a*, its angle α and the modified Froude number $Fn = U_\infty / \sqrt{gL_C}$ are given. Besides of unknown function z(x), there are 32 undetermined parameters in Eq.(1): σ and the fictitious wedge angle β. There are conditions $\int_{-a}^{1+b} \frac{dz}{d\xi} d\xi = 0$, $\frac{dz}{dx}(1) = \beta$ for them.

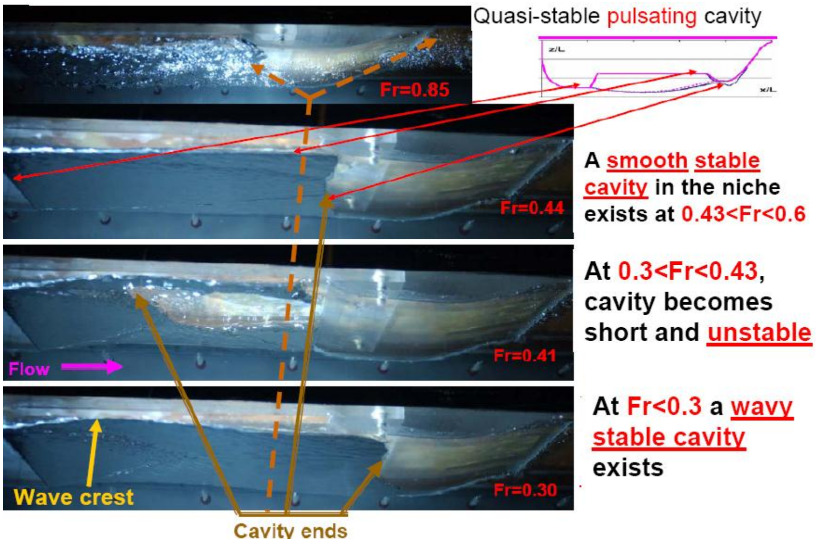


Figure 3: Cavities created under water tunnel ceiling (shapes from 1 to 4); after Arndt at al [4]

Solutions of Eq.(1) show that:

- Cavities of the type 1 correspond to positive σ and have substantial drag penalties. In experiments (like illustrated by Fig.3), such cavities undergo significant tail oscillations.
- Cavities of the type 2 are stable under moderate flow perturbations, have no drag penalty and no air escape from the tail. There are Fn minimum values for their existence. According to approximation by Ivanov et al [5], the length of a cavity behind the cavitator-wedge under flat bottom is limited by $5.537U^2/g$, but for small α, Butuzov found that $l_{max}=3.35U^2/g$ For a cavitator-backward step

under flat plate, this value is, according to linear theory, Fn=0.657 (nonlinear computation by Amromin et al [6] gave Fn≈0.62 for a buttock with a cavitator-step).

- Only very unstable cavities were observed for the lengths corresponding to the computed cavities of the shape type 3 (as illustrated by Fig.3).
- A wavy cavity of thee type 4 can be maintained at smaller Fr. For the Re values of practical interest, a very significant increase of air supply is necessary to jump from the shape type 2 to the shape type 4. A trust was predicted for these cavities (it is explainable because such cavities correspond to $\sigma<0$ and may exist with an excessive air pressure only). Thus, there are three different situations for diverse ranges of *Fr*.

Because this DR technology is based on reduction of the wetted surface area, it is necessary to maximize the hull surface area covered by cavitation. For a 80 m ship moving at the speed of 20km/h, a single cavity of the type 2 length is limited by $3.35U^2/g$ =11m and gives no measurable effect. So, a system of cavities was designed for the bottom. The sketch of such system described in the Butuzov's [7] patent is shown in Fig.4.

For the wavy cavity under flat plate, the drawback was in a big air demand to maintain the cavity. However, as was found in 1970s by Y. Gorbachev, there is a possibility to reduce this demand by locking the air escape from the cavity with a locker/obstacle. Such locker coupled with the backward facing step generates a bottom recess/niche. The design with a single wavy cavity was described by Butuzov, Gorbachev et al in [8]. The design scheme is presented in Fig.5.

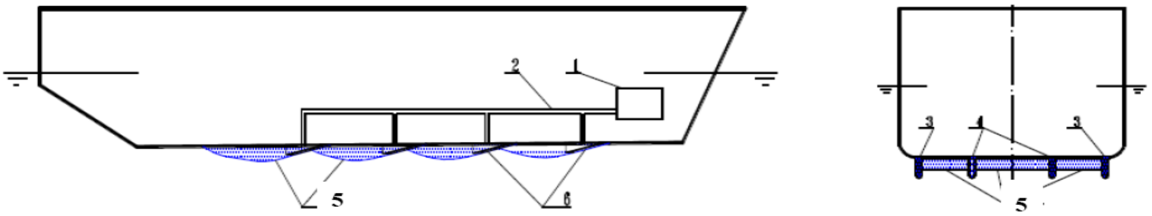


Figure 4 Sketch of a ship with a system of cavities (DRBC scheme 1): 1 - compressor, 2 – pipelines, 3 – side keels, 4 – internal keels, 5 –cavitators-wedges, 6 – cavities. Flow goes from the right.

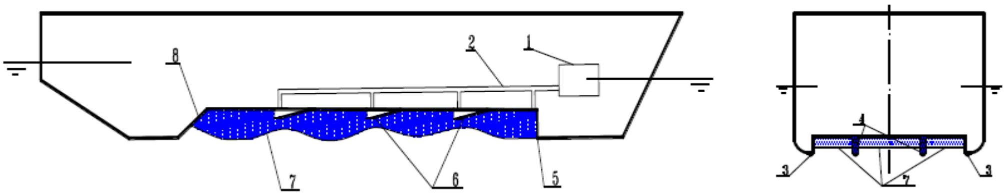


Figure 5 Sketch of a ship with a wavy cavity (DRBC scheme 2): 1 - compressor, 2 – pipes, 3 – side keels, 4 – internal keels, 5 –leading cavitator-step, 6- interior cavitators, 7 – cavity, 8-cavity locker.

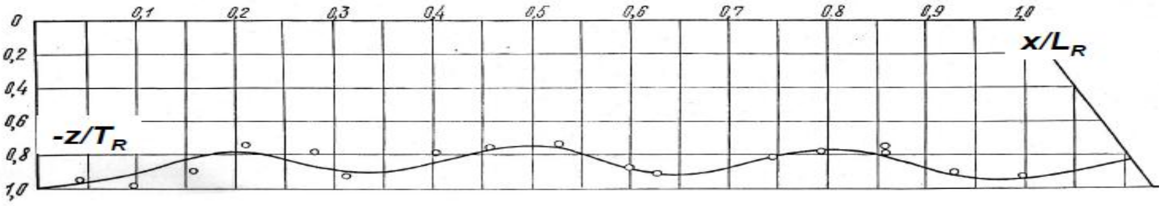


Figure 6: Computed and measured (circles) cavity profile. $U_\infty = \sqrt{gL_C/23}$, flow goes to right

The design problems were solved in the quasi-linear approach similar to the Tulin [9] approach for hydrofoils. A generalization of Eq.(1) was used. The ideal fluid velocity *U* over the hull has been computed using the Hess and Smith [10] method. Locations and sizes of the recess and keels have been given in this problem. The problem solutions (by Gorbachev [11-16]) allowed for predictions of the fundamental trends in drag reduction by wavy cavities. These predictions were validated by water tunnel and towing tank tests (as for the cavity shape in Fig 6). It was shown in experiments that a quite small air supply is sufficient to maintain the cavity and the cavity shape is practically independent on the supply rate. Also, the recess deepness does not influence the wave length and magnitude.

3. TEST RESULTS FOR SHIP MODELS AND SHIPS WITH BOTTOM CAVITATION

The river ships operating at Fr<0.22 were evaluated as the most suitable for retrofit because of a high share of friction in their total drag (over 70%) and a high ratio of the flat bottom area to the whole wetted surface area (from 50÷55% for self-driving ships to 75% for barges). Also, it was cheaper to start full-scale experiments with them. The successful full-scale experience for small-*Fr* full-scale DRBC have related to the river ships.

The evident advantage of the first design scheme is the possibility to keep the hull structures practically unchanged. So, this scheme looks as the best for retrofit of this DR technology to existing ships.

It is evident that the side keels must restrict the air escape from the cavity. The role of internal keels is in augmentation of the ship lateral stability. According to Potapov & Starobinsky [17], two internal keels allow for keeping of 89% of the restoring moment of the initial hull, one keel restores only 75% of it. The cavitator distribution and shape was first predicted by solving an equation similar to Eq.(1), but written for a set of cavitators. Then towing tank tests of models with transparent bottoms were carried out for the final bottom design. As one can see in Table 1, this scheme was applied to 3 diverse hulls. The model test results were confirmed by full-scale tests in Volga river. It was then first confirmed that there is some saturation air supply rate and an excessive air supply does not amplify DR, but there is a DR plateau.

Table 1: Retrofit of multi-cavity DR by ventilated cavitation to river ships in USSR

	Barge	River ship	Two unit train	
		Volgo-Don	Leading unit	Trailing unit
Length (m)	84,6	135,0	96,0	97,2
Beam (m)	14,0	16,5	14,0	14,0
Draft (m)	3,2	3,2	3,5	3,5
Displacement (m^3)	3270	6140	4260	4290
Number of cavitators	7	7	8	8
Height of keels (m)	0,2	0,15	0,15	0,15
Air supply at DR plateau (liter/sec)	137	240	130	130
DR rate	20%	16%	12%	

As shown in Figs.7 (after Butuzov et al, [18]), the reduction of required tug power was about 20%. A 16% power reduction of the self-driven ship was kept with her speed increase up to 20km/h. With a speed decrease, both cavity lengths and drad reduction drop. For running without cavities past cavitators, the additional 6÷7 % power was necessary.

The propellers did not affect the cavity shape in these experiments, but the air escaped from cavity may affect the propeller inflow at small *Fr*. Therefore, small air-suctioning cavitators (shown in Fig. 8) were installed on the hull downstream of the cavity to protect propellers from the escaping air bubbles.

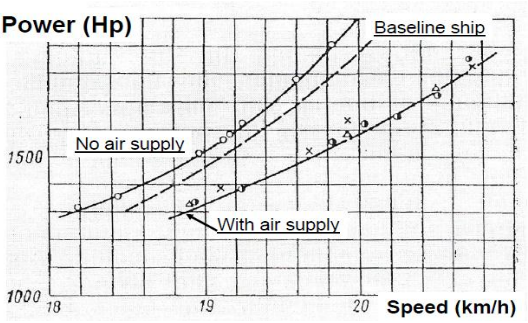


Figure 7 Cavity effect on power required by self-driven ship Volgo-Don. Crests, triangles and circles relate to various Q

Some cavity influence on the propeller-hull interaction exists because a friction reduction is always associated with changes in the hull boundary layer and wake. The efficiency of a propeller designed for a baseline hull can decrease because in the hull effect coefficient $\eta_h=(1-t)/(1-w)$, the wake coefficient w decreases, whereas the coefficient t has an insignificant change. Although this drop is secondary in comparison with the achieved power gain and the propeller redesign is not unavoidable, such redesign may save around 4% of the power.

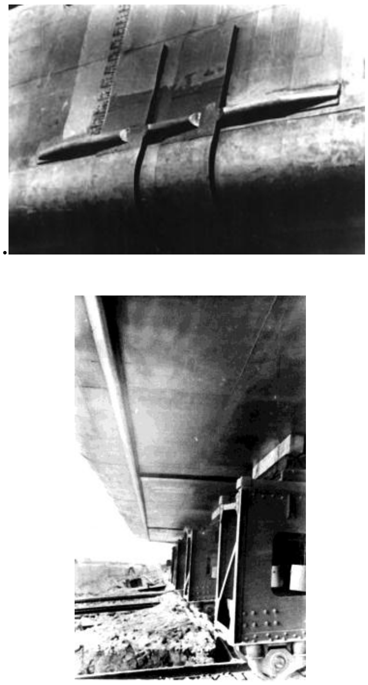


Figure 8 Devices for protection of propellers from air drifting downstream of the cavity (top, described in the 1970 Butuzov's Soviet patent #217980) and the interior cavitators of the ship Volga-Don (bottom)

The maneuverability was not practically affected by DRBC. The circulation radius was kept because reduction of the bottom friction was compensated by the keels drag (as described by Gorbachev and Vyugov [14]).

The route up to complete stop increases, but this route can be controlled by reduction or interruption of the air supply.

Let us note that the conditions of these full-scale tests were very favorable: There were no waves, the ship loading was made without any trim and the 0.2m height keels were sufficient to keep the cavity stability.

However, even for the inland transportation, the keels of used heights would be unable to always protect the cavities always. On the other hand, along the majority of rivers, there are shallow water intervals, where bigger keels would reduce the actual draft and payload.

So, two practical reasons leaded later to a switch to the design with wavy cavities in a bottom recess/niche. First, the challenge of the keel advance will be avoided. Second, many wetted strips between cavities under the bottom reduces the attainable drag reduction rate, whereas the bottoms with wavy cavities have no such strips. It is important to point out that design must be carried out for the expected ship trim (some trim may be caused by cargo location, fuel consumption during the route, etc.). As illustrated by computed cavity shapes in Fig.9 (after Gorbachev [16]), there is a significant trim effect on the distance between cavity and the bottom. So, the danger of the cavity decay must be taken into account: The wave magnitude rises mainly near the recess edges. Indeed, just the trim oscillation due to wave impact in seaway look as the main obstacle for employment of drag reduction by wavy ventilated cavities in seas. The heave oscillation is less influent for ventilated cavities at low Froude number because of a relatively small influence of cavitation number on the cavity shape.

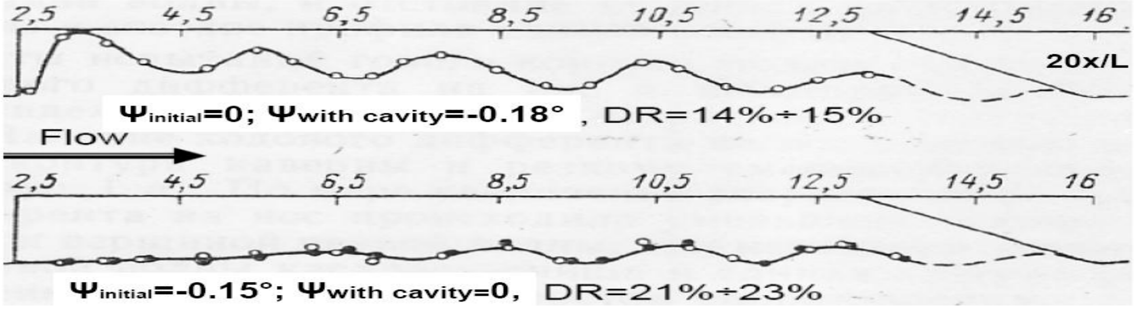


Figure 9 Trim effect on cavity shape and DR for a tanker model at Fr=0.14

The important practical aspect is the cavity creation within such big recess. For its faster creation under a moving ship, a system of interior cavitators perpendicular to the hull diametric plane was designed. The interior cavitators can also generate a system of smaller cavities when the single cavity cannot be maintained. The number of interior cavitators was equal to the number of the waves on the cavity surface, their location (trailing edges) was tuned to the wave descending slope. The wavy cavity creation starts from the successive creations of limited length cavities of the type 2 behind cavitators (first behind the backward step, then behind the first interior cavitator and further downstream.) After creation of such cavity behind the last cavitator, the successive cavity merging starts upstream from the last cavity with jumps of air pressure in the cavity during each merging covering interior cavitators by an expanding wavy cavity. The air demand on cavity creation is smaller than the recess volume for both the barge and its model.

Determination of the full-scale DR rate for wavy cavities was carried out in 1988-1989 for a 1000-ton river barge towed along rivers Belaya and Volga. The barge drag was directly measured by a dynamometer placed in the barge-tug connector. Its data were well matched to the measurement of the engine power (as shown in Fig.10)

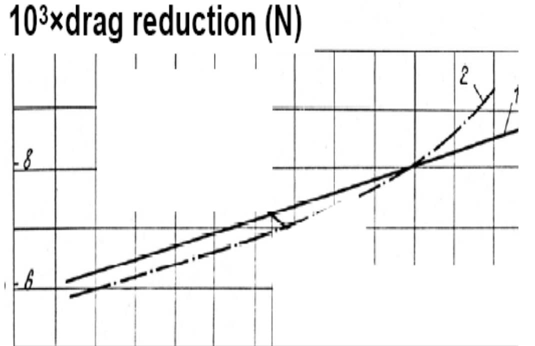


Figure 10: Data of dynamometer (line 1) compared with engine power data (line 2)

The cavity effect on the full-scale barge drag is shown in Fig.11. These data relate to deep water. The river depth decrease down to 3.5 ship draft did not affect DR rate, but its further decrease down to 1.7 ship draft cut more than 30% of DR due to a decreasing fraction of friction in the total drag.

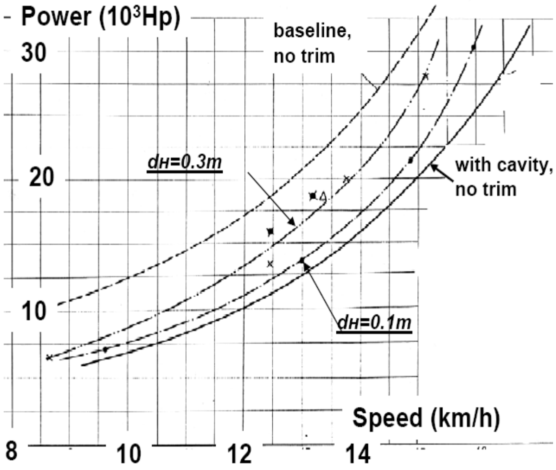
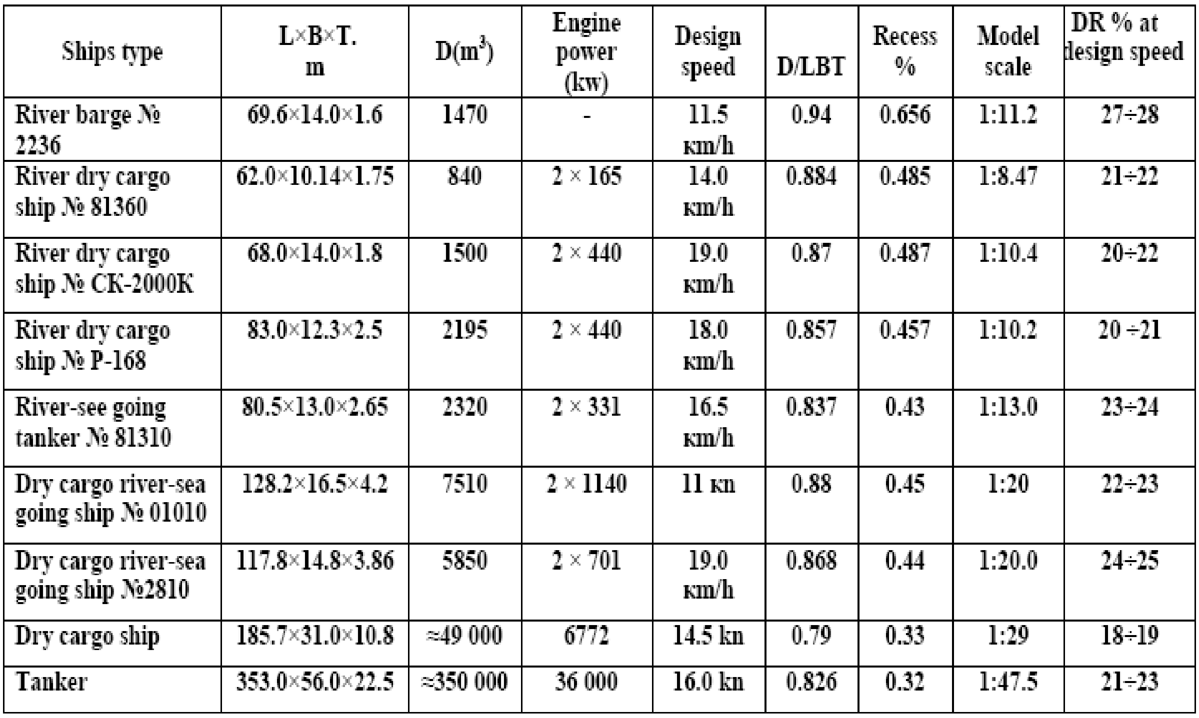


Figure 11 Resistance of a 1000-ton barge with DRBC. For the difference of stern and bow sinkage dh=0.3m, the barge were towed at various air supply rates and methods

The described results had no an extended application because of a crisis of river cargo shipbuilding in Russia in the following years, but several design projects (mainly, projects of Engineering Center of Shipbuilding from St-Petersburg) were recently funded and model tests have been carried out in towing tanks of Krylov Ship Research Institute. One of models is shown in Fig.12. The list of these models with their main characteristics and achieved DR is given in Tab.2. These models were selected from previously existing ships as the most suitable for DR by air cavitation with wavy cavities because of their high fullness D/BLT. Their design *Fr* values were between 0.12 and 0.205.

Figure 12 Model 01010 of a cargo ship with the recess for wavy cavity, interior keels and cavitators in Krylov Ship Research Institute.

Table 2: Recent model tests for ships with wavy cavities in Russia



Ships type	L×B×T. m	D(m³)	Engine power (kw)	Design speed	D/LBT	Recess %	Model scale	DR % at design speed
River barge № 2236	69.6×14.0×1.6	1470	-	11.5 кm/h	0.94	0.656	1:11.2	27÷28
River dry cargo ship № 81360	62.0×10.14×1.75	840	2 × 165	14.0 кm/h	0.884	0.485	1:8.47	21÷22
River dry cargo ship № CK-2000K	68.0×14.0×1.8	1500	2 × 440	19.0 кm/h	0.87	0.487	1:10.4	20÷22
River dry cargo ship № P-168	83.0×12.3×2.5	2195	2 × 440	18.0 кm/h	0.857	0.457	1:10.2	20 ÷21
River-see going tanker № 81310	80.5×13.0×2.65	2320	2 × 331	16.5 кm/h	0.837	0.43	1:13.0	23÷24
Dry cargo river-sea going ship № 01010	128.2×16.5×4.2	7510	2 × 1140	11 кn	0.88	0.45	1:20	22÷23
Dry cargo river-sea going ship №2810	117.8×14.8×3.86	5850	2 × 701	19.0 кm/h	0.868	0.44	1:20.0	24÷25
Dry cargo ship	185.7×31.0×10.8	≈49 000	6772	14.5 kn	0.79	0.33	1:29	18÷19
Tanker	353.0×56.0×22.5	≈350 000	36 000	16.0 kn	0.826	0.32	1:47.5	21÷23

For wavy cavities, unlikely to a system of cavities, the DR rates even slightly increase a *Fr* decrease because the cavity will not be shorten, but a 20÷30% speed increase over the design speed will destroy the cavity due to increase of the wave magnitude. According to the model test results, for the tanker from Tab.2, the DR would not be affected by waves in sea state 5 and it would drop from 18% down to 7% in sea state 6. In sea state 7, the cavity of type 4 in the recess will be destroyed and the additional drag would appear.

For tested models of river ships, the trim at *Fr* corresponding to the design speeds in Tab.2 corresponded to 0.1m difference of bow and stern sinkage. The trim corresponded to 0.15m for models of river-sea going ships, 0.8m for the model 49080 ton sea ship and 1m for the model of the tanker.

The trim values are so important because the most significant limitations on employment of wavy cavities rise from the trim effect on them. This effect is associated not only with the sea wave impact: The trim variation between loaded and unloaded 350000 ton tanker is 0.95°. The single wavy cavity under such trim is destroyed into a system of short cavities that are barely sufficient to keep the hull drag around its baseline value: The recess without air cavity gives a substantial additional drag (it may be over 20% for self-driven ships and up to 50% for towed barges). The similar situation takes place with the model of a 49080 ton bulker. So, changes in the ballast system or other substantial design changes must be done to make it profitable for the entire shipping the ship with 18% DRBC at the design speed.

Independently on the above-mentioned recent Russian studies, a Model 5694 of a landing ship with a single bottom cavity (shown in Fig.13) was designed in US and towed in the linear tank of David Taylor Model Basin. This model combines a niche with skegs advanced substantially below the bottom; so, it was a hybrid of the first and second design schemes. The model length to beam ratio is 4.5/1.1, the length to draft ratio was varied from 18 to 22.5. The design *Fr* of this model was around *Fr*=0.5. The bottom niche was designed to keep DRBC of a 90 meter ship up to sea state 5. A detailed description of this recent work related to moderate *Fr* was published by Amromin et al [6, 19] in easily accessible sources. Therefore, here we point out only its main results. As shown in Fig.14, DRBC up to 25% was measured in calm water. The power spent on air supply was around 1% of the power spent on the model towing.

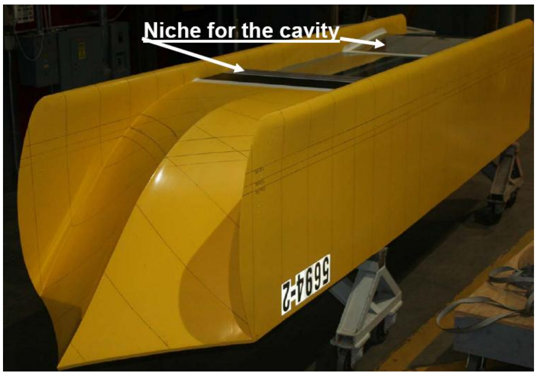


Figure 13View of overturned Model 5694 in David Taylor Model Basin

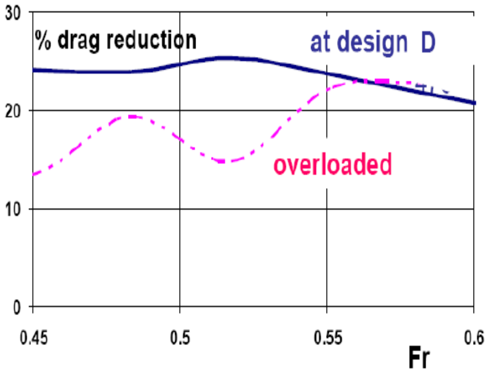


Figure 14 Calm water drag reduction of Model 5694 at the design load and 26% overload

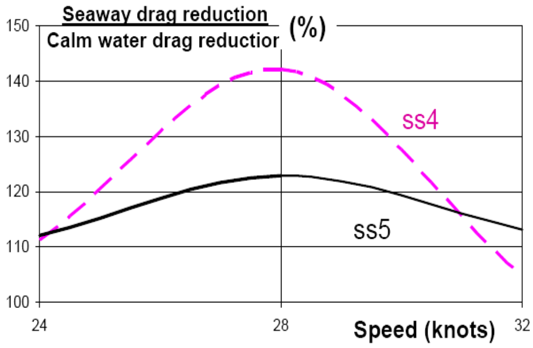


Figure 15 Drag reduction in seaways compared to the calm water drag reduction

As shown in Fig.15, a ship with the cavity of type 1 can even amplify its DR ratio in waves (the waves in the model tests corresponded to sea states 4 and 5 for a 90 meter ship). It happens because the ship additional drag in waves with the bottom cavity is smaller than the baseline ship additional drag. So, up to 35% of DRBC in sea state 4 is expected, but with the transition from sea state 4 to sea state 5, the big cavity-destroying waves appear more frequently and their appearance reduces the DRBC rate.

Some aspects of DRBC were clarified neither by Russian studies, nor by American studies yet. For example, the model tests for river ships manifested a substantial mutual influence of cavities: for the two-barge train, the power reduction was 40% smaller than the self-driven ship shows, whereas the percentage of wetted surface reduction by cavities was only 25% smaller. A similar decrease of effectiveness of DRBC for a train of two towed models 5694 was found at higher *Fr*. The nature of such decrease is not clear yet.

Nevertheless, the basic knowledge necessary for design with DRBC is already achieved. At this point, the design became rather a multidisciplinary optimization problem with the comparative cost analysis of shipping and manufacturing expenses, with taking into account that the profit is not limited by the fuel cost and a fuel saving allows for a payload increase; that the surface under cavity is tolerant to biofouling and this reduce expenses on its periodical cleaning in dock, etc. However, such analysis goes out of the topic of this paper.

4. REMARKS ON SHIP DRAG REDUCTION BY MICROBUBBLES

Besides of bottom cavitation, there is another technology based on hull ventilation: The microbubble drag reduction (MDR). During four decades of experiments, MDR up to 80% has been measured in many laboratories on small flat plates (as illustrated by Fig.16 plotted with data of Merkle & Deutsch [20]).

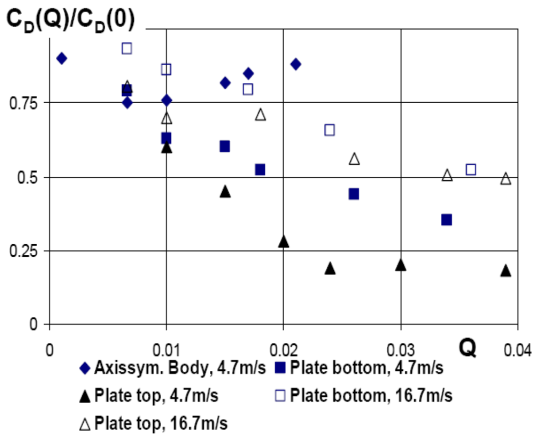


Figure 16 Effects of air supply Q and flow speed on MDR for plates with air ejections on their different sides and for an axisymmetric body with air ejections.

No special upstream devices (like cavitators) are necessary for MDR. So, this technology has looked very attractive for retrofit to existing ships, though the MDR rate decreases with the flow speed. However, as found by Sanders et al [21] (and shown in Fig. 16), the positive effect sharply decreases also with the distance from the ejection point. Besides, for bodies, as one can see in Fig.17, MDR rates drop with an increase of the air supply.

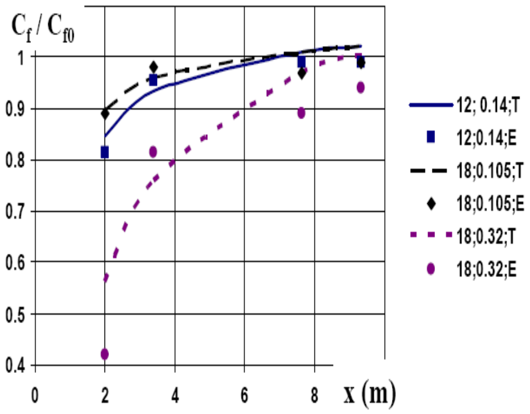


Figure 17 Computed (by Amromin [22], lines) and measured (by Sanders et al, [21]) MDR ratios C_f/C_{f0} along the same flat plate. The first numbers in the legend indicate the flow speed (m/s). The second numbers indicate the air volume concentration.

As explained by Amromin [22] with use of integral boundary layer momentum equation

$$\frac{d(\rho^*\delta_2)}{\rho^* dx}+\frac{2\delta_2+\delta_1+\left(\frac{1}{\rho^*}-1\right)\delta-\delta_2 M^2}{U}\frac{dU}{dx}=\frac{C_f}{(4\rho^*-2)} \quad (2)$$

this drop occurs because the assistant increase of the wake thickness leads to an increase of the form resistance. In Eq.(2), δ, δ_1 and δ_2 are the boundary layer thickness, its displacement thickness and its momentum thickness, U is the velocity on the layer outer boundary, ρ* is the ratio of the density of water-air mixture to the air density, C_f is the local friction. Because the air volumetric concentrations used in MDR are quite high and the corresponding air mass concentration is between 0.0001 and 0.001, the local sound speed can be very low (as seen in Fig.18) and the local Mach number M ceases to be negligible. The significance of the coupled effects of the pressure (velocity *U*) gradient and the flow compressibility on MDR is evident from Eq.(2), but this effect absents in the numerous flat plate experiments. The analysis [22] also pointed out the coupled decrease of medium density in the boundary layer and increase of its thickness as the main mechanism of MDR.

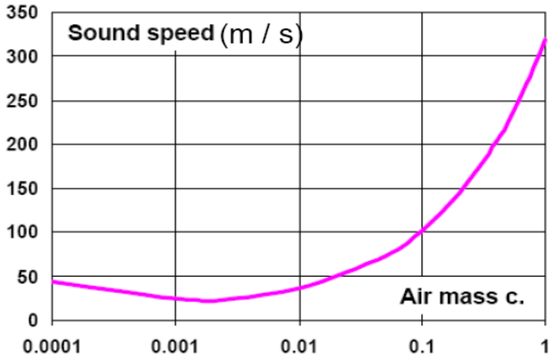


Figure 18 Sound speed versus air mass concentration in homogenous air-water mixtures

With insufficient understanding of MDR mechanism no attempt of apply MDR to ship hulls has been made in USA.

In Europe, the 110m inland navigating tanker “Till Deymann” with the micro-bubble ejection was recently tested. According to Thill [23], “*the micro bubble lubricated test ship “Till Deymann” showed hardly any improvement in terms of saved propulsion power. Including the energy required to actively provide the air by compressors, even a negative energy saving was measured*”. The following model test at the same *Fr* (but at different M) in the depressurized towing tank of MARIN confirmed the little improvement of the ship’s total drag by MBR. The contradiction of the results for the ship and its model to the flat plate results were noted by Thill [23]. Nevertheless, the mechanical basis of this contradiction was not found and he wrote that “*it turned out that micro bubbles are somewhat more far from practical applications in the maritime sector”.*

On the other hand, Sato et al [24] reported a 30% friction reduction for a ship model in Japan, but the assistant form resistance increase reduced DR to 20% and the energy spending on air supply put the total DR down to 12%. Kato reported in 2003 a real ship experiments with no certain MDR. Kodama announced the total 5% DR for a 120 meter length ship with microbubbles in 2009.

The more recent Mitsubishi report on 25% energy saving for a ship with MDR is difficult to evaluate. There are two issues for its evaluation: first, besides of MDR two other innovations were applied there; second, it will take a time to see a biofouling effect on the bottom perforation with its consequences to MDR, as well as other impacts of shipping.

5. CONCLUSIONS

Drag reduction by bottom ventilated cavitation appeared to be the most effective technology of ship drag reduction. Also, this technology is environmentally friendly.

Selecting a design scheme for DRBC, it is necessary to take into account several factors. The evident advantage of the first scheme is its simplicity. The use of this scheme does not bring principal changes in ship's construction and there is a possibility of retrofit of this scheme to the existing ships (already proven in Soviet Union in 1960s). However, the advance of the keels and inclined plates down the bottom can become a serious drawback because many rivers have shallow parts. A draft reduction (necessary to prevent running aground) would reduce the ship's cargo-carrying capacity and affect the economical results. So, the use of the first design scheme of DRBC is expedient on large sea-going ships: At least 10-15% reduction of the fuel consumption by them is the very achievable aim, whereas effectiveness of this scheme for river ships depends on the depth of the fairway on the operation line.

The second design scheme of DRBC requires more changes in the ship construction, but it can be essentially more effective. The bilge and longitudinal keels protrude insignificantly below the bottom's surface (for river ships their height is about 0.05m). So, this scheme increases the reliability of the device and does not require the reduction of the ship's cargo-carrying capacity when passing shallow water sections. Possible fuel reduction during all service life of the ship can amount to 20-30% for river ships and 15-25% for very large sea-going ships.

In 2013-2014, Engineering Center of Shipbuilding and Krylov Ship Research Institute will carry out the full-scale tests of a 4000-ton river-sea going bulker: The ship will be first tested with its traditional hull shape, then the hull will be modified for the second design scheme.

Hybrids schemes are also promising. In particular, they can keep drag reduction by cavitation in wavy seas and at high speeds.

All above estimations are valid for ships with fresh painted hulls. During the service life ship hulls are exposed to fouling, corrosion, surface deformations involving a considerable increase in their hydrodynamic resistance. Air cavities under the bottom reduce these undesirable effects. For this reason, in actual operating conditions the efficiency of the device is increased 1.3-1.7 times as compared to that for ships with fresh painted hulls.

There is too early to make conclusions on the effectiveness of microbubble drag reduction for ships. First, a proven technology of design and model test scaling for ships with MDR does not exist and currently the design deliverables are not stable. Second, the reported full-scale MDR rates are quite small and the impact of real shipping conditions on MDR was not reported yet. Moreover, sometimes employed combination of MDR with other ship improvements makes it impossible to evaluate the results at all.

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