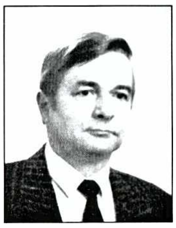

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Research on effectiveness of separation process of oil-water emulsion in a hydrocyclone

SUMMARY

In the paper shortly presented are phenomena of dynamic separation process which occurs in a novel hydrocyclone which separates two, non-mixing together liquids. Measurements of the oil/water separation effectiveness performed at different testing parameters for two configurations of the model hydrocyclone elaborated by Maritime University in Szczecin are described.

Also, oil particle size distributions before and behind the hydrocyclone, obtained by means of a particle size meter based on laser light difraction method, developed by Malvern Instruments Ltd, are also presented.

INTRODUCTION

In the last years increasing pollution of the marine environment has become a great problem. Oil pollutants appear in sea waters a.o. during regular operation of ships, i.e. as a result of discharging of oiled-up water from bilge, engine room and holds directly to sea. However rigorous execution of MARPOL convention provisions has caused that amount of harmful oil pollutants decreases year after year [2,5,9,11,12]. The hydrocyclones for liquid/liquid separation, rather rarely used in petrochemical industry, are today commonly applied in oil drilling and production platforms as well as special pollution fighting ships.

Hence there is a room for implementation of such devices also in typical transport ships, for instance:

- ★ as an preliminary element of a two-stage oil separator for separating oiled-up bilge and ballast water
- ★ separating solid particles and water from lubricating oil or fuel oil.

Liquid-from-liquid separation process in a hydrocyclone

Motion of liquid in a hydrocyclone is different from that in a centrifugal separator [7, 8].

In the separator all amount of its drum's charge rotates, together with it, with a uniform angular speed, and the relationship : $V_t/r = K_C$ is then fulfiled. In Fig.1 this is graphically represented in the form of the curve I. Motion of liquid in a hydrocyclone (see e.g. Fig.2) can be described by the following relationship :

$$V_t \cdot r^n = const = K_{II} \qquad (1)$$

Curve II (Fig.1) is its graphical representation. The exponent n is usually within the range : $0 < n \leq 1$. As the rotating liquid particle approaches the cone axis (i.e. as r decreases) the tangential flow velocity V_t increases and the static pressure drops.

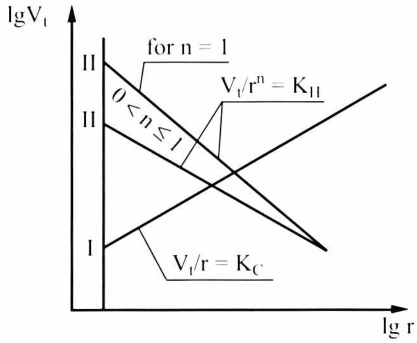

Fig.1. Liquid motion relationships in a centrifugal separator (curve I) and in a hydrocyclone (curve II)

Requirements to be fulfilled by the hydrocyclones separating oil (oil products) from water, were described by J.Listewnik [1, 6] who determined their design dimensions i.e. the hydrocyclone's diameter D, inlet diameter D_{in}, outlet diameter D_{ol} height of cylindrical part, H, height of conical part, h, and cone angle α. The basic difference between a conventional hydrocyclone separating solid particles and a liquid/liquid hydrocyclone consists in a opposite ratio of the outlet and overflow diameters.

In order to obtain the possible highest effectiveness of the separation process of two, non-mixing together, liquids, which occurs in a liquid/liquid hydrocyclone, its design and velocity of oil particles

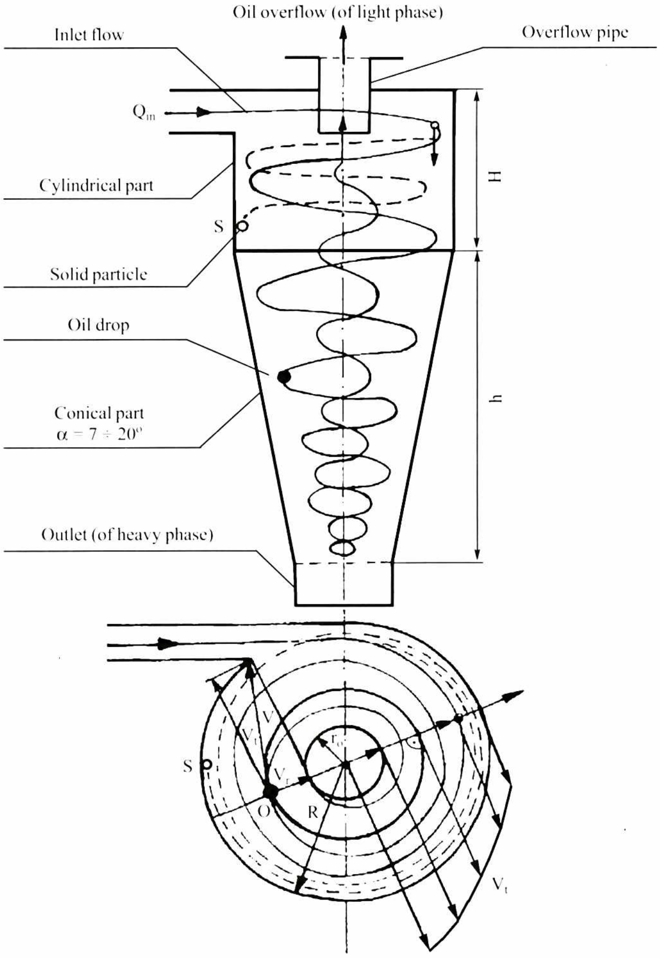

Fig.2. Image of oil particle trajectory within hydrocyclone

should be so selected as to eliminate second dispersion of oil drops. The second dispersion of drops is dependent a.o. on : inlet velocity, its increment during spiral flow within hydrocyclone, as well as of a design solution, i.e. the cone angle α, and cylindrical part height H. Out of the physical parameters influencing the dispersion the following ones are of the greatest influence : the input flow Q_{in}, inlet diameter D_{in}, and overflow ratio Q_{of}/Q_{in}. In separation mechanism description a simplified, two-dimensional model is usually assumed, together with relevant simplifying assumptions. In Fig.2 presented is a simplified model of trajectories of the solid particles (S), and of oil drops (O), as well as a distribution - over hydrocyclone's height - of the tangent velocity V_t.

Due to tangential position of the inlet supplying the hydrocyclone with the flow of the velocity V_t, the centripetal acceleration field of particles occurs that, together with the radial velocity component V_r, makes the oil drops (O), as that lighter, moving towards the hydrocyclone's axis.

In the simplified model the equilibrium of the centripetal force and the drag, acting on the oil particle (O), is assumed. On the basis of such model the minimum diameter of the oil particle separated in the hydrocyclone can be determined, as follows [15] :

$$d_o = \frac{3\sqrt{2}}{V_t}\sqrt{\frac{r(R-r)\cdot\mu_w\cdot V_a}{(\rho_w-\rho_o)\cdot h}} \qquad (2)$$

where :

- d_o – oil particle (drop) diameter [m]
- ρ_w, ρ_o – water and oil density, respectively, [kg/m^3]
- μ_w – dynamic water viscosity of [Pa · s]
- V_t – tangential velocity [m/s]
- V_a – axial velocity [m/s]
- h – height of conical part [m]
- R – external radius [m]
- r – internal radius [m].

Calculations of flow within a hydrocyclone comprise many simplifications; a.o. neglected are the phenomena occurring in the boundary layer and those of the second dispersion which occurs at very high inlet flow velocities which increase further when passing to a smaller radius of spiral motion towards the hydrocyclone's axis.

This is a reason to investigate effectiveness of the separation process occurring within a hydrocyclone, by means of its real model.

INVESTIGATIONS OF OPERATIONAL EFFECTIVENESS OF A HYDROCYCLONE (Task 1)

Test stand

The liquid/liquid model hydrocyclone (WSM) of an unconventional design (Fig.4), elaborated by a team of the Maritime University of Szczecin, was the main element of the test stand shown in Fig.3.

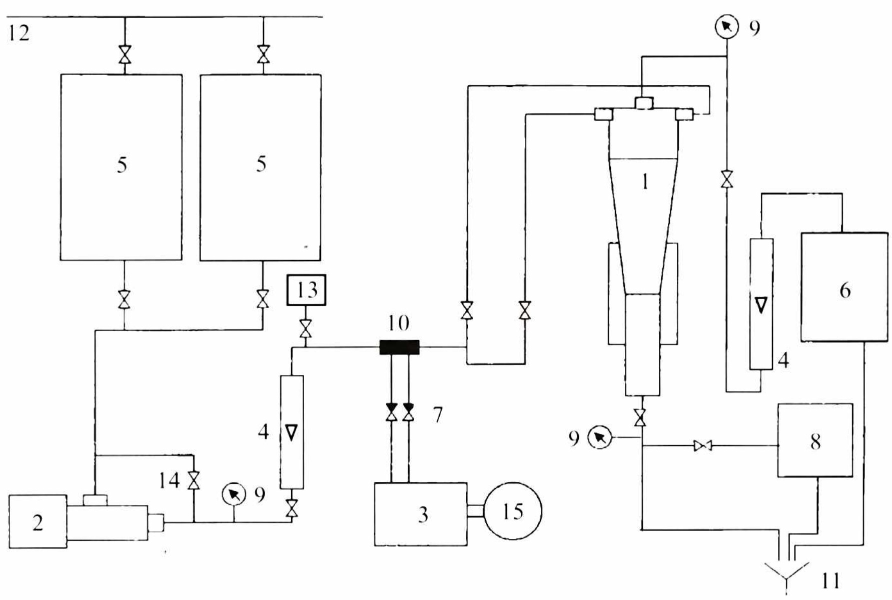

Fig.3. Block diagram of the test stand
1 – liquid/liquid model hydrocyclone, 2 – screw pump of 5 m³/h capacity, 3 – plunger metering pump of ND type, 4 – rotameter of 0 ÷ 6 m³/h capacity, 5 - water tank of 0.5 m³ volume, 6 – recovered oil tank of 50 dm³ volume, 7 – non-return valve, 8 – Fluoritest or Horiba meter, 9 – manometer, 10 – sight glass, 11 – gutter, 12 – supply terminal from general water suply network, 13 – oil plunger feeder of 2.5 dm³ volume, 14 – valve, 15 – electric motor

Program and course of the investigations

The investigations of the model hydrocyclone in question were aimed at measurements of its oil separation effectiveness under the following assumptions :

- maintaining the water inflow rate Q_w constant, at the constant inlet oil dosage Q_o
- changing the overflow pipe diameter D_{of} at simultaneous changing the angle α and the height h, of the hydrocyclone's cone (Fig.4).

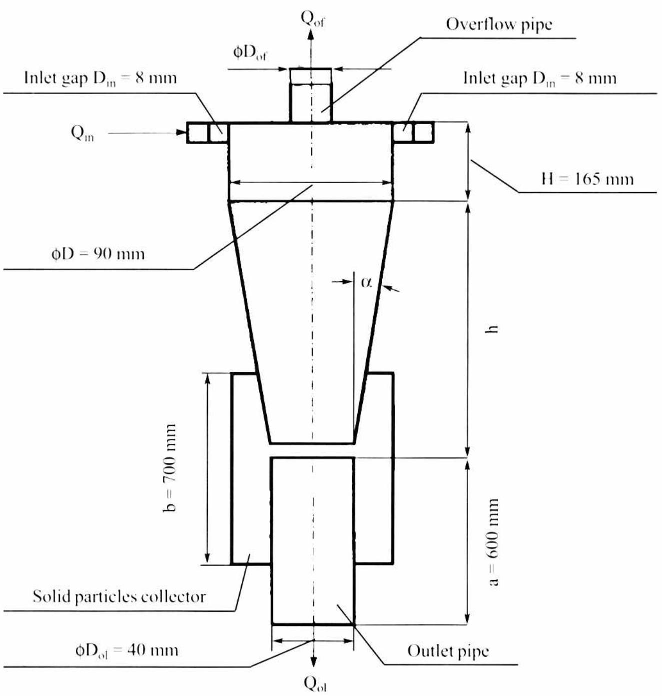

***Fig.4.** Main dimensions (parameters) of two investigated configurations of the liquid/liquid model hydrocyclone*

For determining the effectiveness of oil separation in the hydrocyclone, η, according to the following definition :

$$\eta = 1 - \frac{c_{ol}}{c_{in}} = 1 - \frac{0.0016}{0.1} = 0.984 \tag{3}$$

the oil concentration in the outlet water (heavy phase), c_{ol}, was measured. The oil content was under current control performed by means of FLUORITEST device, and then it was exactly measured in the outflow water, i.e. after separation, with the use of HORIBA OCMA 220 meter.

The investigations were carried out for three different media : two grades of fuel oil and a lubricating oil whose properties are given in Tab.1.

***Tab.1.** Properties of the used fuel and lubricating oils*

Properties	Lubricating oil LO	Light fuel oil MDO	Heavy fuel oil HFO
Density at 20°C, [cSt]	0.902	0.875	0.962*
Kinematic viscosity at 40°C, [cSt]	97.46	14.72	191.9*
Dynamic viscosity at 40°C, [Pa · s]	109.55	17.08	184.6*
Water content [%]	0.1	0.1	3
Ignition temperature, [°C]	203	57	101

**this was measured at 50°C temperature*

During metering the heavy fuel oil was heated to 70°C to obtain an appropriate flowability.

The investigations consisted in :

Task 1 – determination of the oil concentration at outlet from the hydrocyclone during metering, successively, the light oil (MDO), heavy fuel oil, and lubricating oil, at their constant concentration of 0.1 % at inlet,

Task 2 – determination of oil particle size distributions.

Results of Task 1 are presented in Tab.2 and 3.

***Tab.2.** Results of oil concentration measurements for the hydrocyclone of the dimensions : D_{of} = 10 mm, h = 410 mm, α = 7°*

Configuration I

Oil concentration at inlet c_{in} [%]		0.1								
Liquid flow rate Q_{in} [m³/h]		2								
Oil dosage Q_o [dm³/h]		2								
Medium type		**Lubricating oil**			**Light fuel oil**			**Heavy fuel oil**		
Overflow ratio Q_{of} / Q_{in} [%]		10	12.5	15	10	12.5	15	10	12.5	15
Outlet pressure p_{ol} [bar]		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Overflow pressure p_{of} [bar]		0.7	0.6	0.5	0.7	0.6	0.5	0.7	0.6	0.5
Oil concentration at outlet, c_{ol} [ppm]	From Fluoritest device	16	15	12	9	7	6	3	2	1
	From Horiba meter	28	23	18	24	21	19	23	17	8
Separation effectiveness η [-] acc. (3)		97.2	97.7	98.2	97.6	97.9	98.1	97.7	98.3	99.2

***Tab.3.** Results of oil concentration measurements for the hydrocyclone of the dimensions : D_{of} = 8 mm, h = 820 mm, α = 3.5°*

Configuration II

Oil concentration at inlet c_{in} [%]		0.1								
Liquid flow rate Q_{in} [m³/h]		2								
Oil dosage Q_o [dm³/h]		2								
Medium type		**Lubricating oil**			**Light fuel oil**			**Heavy fuel oil**		
Overflow ratio Q_{of} / Q_{in} [%]		10	12.5	15	10	12.5	15	10	12.5	15
Outlet pressure p_{ol} [bar]		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Overflow pressure p_{of} [bar]		0.58	0.52	0.48	0.58	0.52	0.48	0.58	0.52	0.48
Oil concentration at outlet, c_{ol} [ppm]	From Horiba meter	21	21	16	36	14	8	13	23	55
Separation effectiveness η [-], acc. (3)		97.9	97.9	98.4	96.4	98.6	99.2	98.7	97.7	94.5

Discussion of results

The separation effectiveness of oil from water/oil mixture, calculated for both configurations was contained between 97.2% and 99.2%, except of two results: 94.5% and 96.4%

Most results obtained for the second configuration exceeded those for the first configuration. However in general, the obtained results regarding the separation effectiveness can be deemed satisfactory.

And, from the test results of the first configuration, the growing separation effectiveness along with the overflow rate increasing from 10% to 15%, could be clearly observed.

For the second configuration such relationship was not so distinct as it occurred for the light fuel oil only, whereas for the heavy fuel oil an opposite tendency was observed.

Therefore, it is hard to conclude that the obtained results of the tests performed with the three, differring to each other, oils, are sufficient for an unambiguous determination of the influence of the changed parameters of the hydrocyclone in question on its effectiveness.

DETERMINATION OF PARTICLE SIZE DISTRIBUTIONS (Task 2)

Measurement method

To investigate particle size distributions a meter of Malvern Instruments Ltd. was applied. The applied instrument operates on the basis of analyzing particle size distribution by means of the laser diffraction method based on laser light dispersion. It makes particle sizing in the liquid sample possible (in compliance with ISO standard 13320/01).

By using the method it is possible to determine both quantitative and volumetric distributions of particles within the size range of 0.01÷2000 μm [13, 14].

Measurements of particle size distributions for the light fuel oil (MDO) were performed at the flow parameters of the test stand with the installed hydrocyclone of the second configuration, given in Tab.4.

Tab.4. *The flow parameters of the test stand installation during measurements of particle size distributions of light fuel oil*

Liquid flow rate Q_{in} [m^3/h]	2
Overflow ratio Q_{ol}/Q_{in} [%]	10
Screw pump pressure [bar]	0.8
Oil concentration at inlet, c_{in} [%]	0.1
Outlet pressure p_{ol} [bar]	0.4
Overflow pressure p_{ol} [bar]	0.58
Oil concentration at outlet, c_{ol} [%]	0.0016
Separation effectiveness η [-] acc. (3)	0.984

The taken samples were acidified with 10% sulfuric acid to obtain the hydrogen ion concentration pH > 1. Such sample reaction was necessary to maintain its stability by preventing the oil particles dispersed in water to aggregate again.

Results of measurements

The volumetric and quantitative size distributions of oil particles, measured behind the hydrocyclone in question, are presented in Fig.5 [14]. And, in Fig.6 compared are the volumetric particle size distributions of the light fuel oil (MDO) before and behind the hydrocyclone.

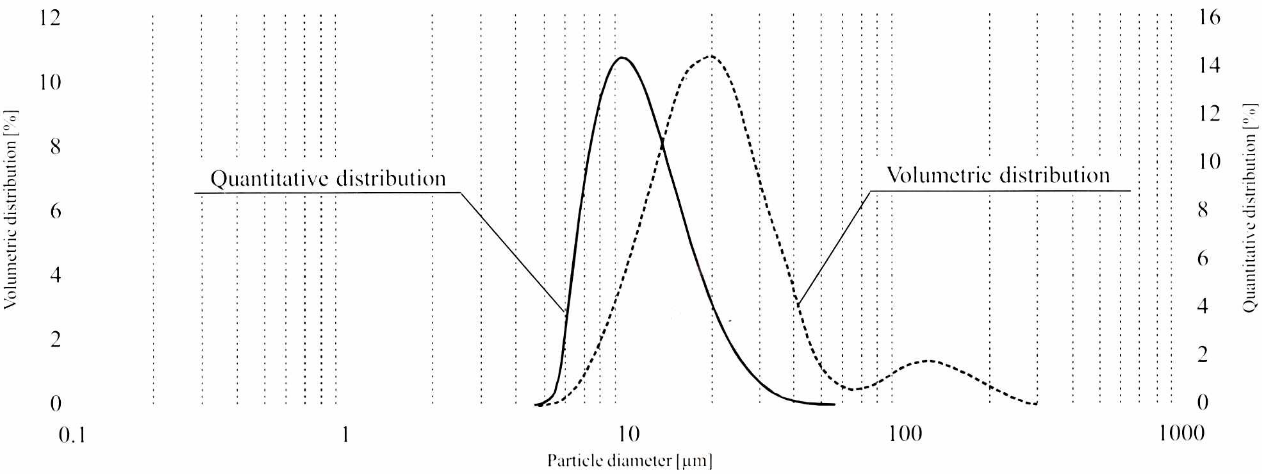

Fig.5. *Particle size distributions of the light fuel oil (MDO), determined behind the hydrocyclone*

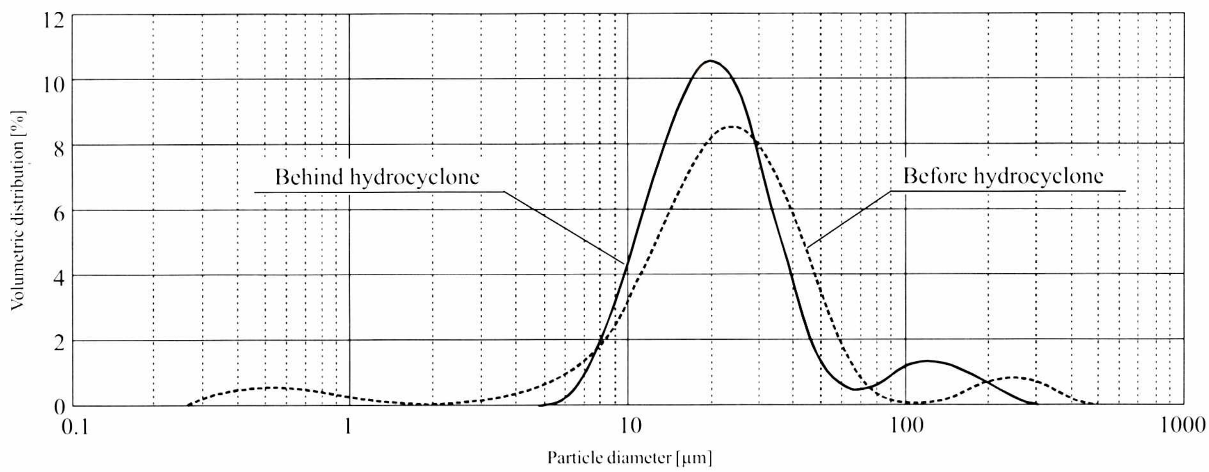

Fig.6. Volumetric particle size distributions of the light fuel oil (MDO), determined before and behind the hydrocyclone

The volumetric distribution function $f_v(x)$ was determined according to the following formula :

$$f_v(x) = \Delta m_i d_i^3 \tag{4}$$

where :

Δm_i – i-th distribution interval of oil particle diameter
d_i – arithmetic mean diameter of oil particles in i-th interval.

The separation effectiveness η calculated from the formula (3) amounted to 0.984.

Disscussion of results

As it results from Fig.5 two distinct oil particle size distributions : quantitative and volumetric, can be observed. The first of them is contained in the interval of 5÷40 μm, with one maximum of 14% at 10 μm. Whereas the volumetric one, contained in the interval of 5÷200 μm, has two extrema in the points : (20 μm ; 11%) and (120 μm ; 1%).

The comparison of the volumetric distributions for the samples taken before and behind the hydrocyclone (Fig.6), shows two common sets of oil particles : that in the interval of 60÷300 μm (of 1% share), and that in the interval of 20÷25 μm (of 9 ÷ 11% share).

For the case „before the hydrocyclone" a small dispersion of the particles within their size interval of 0.25 ÷ 1.5 μm (of 0.5% share), was revealed. In the case „behind the hydrocyclone" i.e. after oil separation, no such small particles was observed. The smallest one was of 5 μm in size, at most.

Therefore it can be stated that the hydrocyclone in question separates effectively, from water/oil emulsion, the light oil particles smaller than 5 μm, reducing the oil concentration from 1000 ppm to 16 ppm (i.e showing 98.4 % oil separation effectiveness).

CONCLUSIONS

- The obtained research results can be deemed satisfactory as the measured oil concentration at outlet from the hydrocyclone are close to that permissible (15 ppm) for dump water according to the MARPOL convention. Only in a few cases the measurement results exceeded this limit.
- From the performed measurements (Tab.2 and 3) it results that the influence of the cone angle change from 7° to 3.5° on the separation effectiveness of the hydrocyclone is small.
- However it is rather not possible, at present, to offer any unambiguous conclusions from the presented research as the number of the flow tests carried out with the liquid/liquid hydrocyclone in question was too small. Therefore such investigations should be continued to obtain reliable separation effectiveness characteristics for the hydrocyclones of optimum design and flow parameters.

Appraised by Jerzy Listewnik, Assoc.Prof.,D.Sc.

NOMENCLATURE

c_{in} – oil concentration at hydrocyclone's inlet
c_{ol} – oil concentration at hydrocyclone's outlet
Q_{in} – liquid flow rate (input flow), $Q_{in} = Q_w + Q_o$
Q_o – oil flow rate (oil dosage)
Q_{of} – oil overflow rate (of light phase)
Q_{ol} – outlet rate (of heavy phase)
Q_w – water flow rate
V – flow velocity of the liquid
V_a – axial flow velocity
V_r – radial component of the velocity V
V_t – tangential component of the velocity V
r – radius of the liquid spiral motion ($r_o \le r \le R$)

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Miscellanea

TOP KORAB in 2002

The Society of Polish Naval Architects and Marine Engineers (TOP KORAB) acts in two regions : of Gdańsk and Szczecin. In the last year 6 club meetings were arranged by TOP KORAB Division of Gdańsk, devoted to the following topics :

- activity and development of Polish Register of Shipping
- medal engraving art. developed in Polish shipbuilding industry, especially in Gdańsk Shipyard
- position of Polish shipbuilding industry against that of world economy
- construction of the newest product carrier built in Gdynia Shipyard
- proposals of logistics firms for shipbuilding industry
- inspirations connected with creation of the interesting book **„Architecture of non-passenger ships"** by Prof. Andrzej Lerch.

A visit was also held in the Research and Development Centre, Marine Engineering Centre in Gdynia, during which activities of the Centre as well as the equipment of its laboratories and workshops, were presented.

Also, sightseeings of the Gdańsk Shiprepair Yard „Remontowa", Gdynia Shipyard and Northern Shipyard in Gdańsk were organized where visitors had an occasion of being acquainted with the achievements which have been reached so far, as well as with current work carried out in the enterprises.

In Szczecin region 3 club meetings were arranged dealing with :

- activity of the Shiprepair Yard „Gryfia" in Szczecin
- domestic and worldwide activities of Polish Register of Shipping
- environmental pollution in the light of MARPOL convention binding the shipping companies.

Also, a conference was held on the occasion of 10th anniversary of commencement of TOP KORAB activity in Szczecin region.