A proposal of ship gas-turbine driven waterjet propulsion – preliminary considerations

Wiesław Próchnicki, Assoc.Prof.,D.Sc.

ABSTRACT

In the paper are presented preliminary considerations concerning the efficiency of waterjet ship propulsion system, as well as the calculation of main dimensions of waterjet channel.The friction and momentum losses of the flow channel have been roughly estimated by using Fliegner's equations. An important conclusion is confirmed that the summary losses are inversely proportional to square of ship velocity (~1/u^2). On the other hand the ship propulsion power is directly proportional to third power of ship velocity (~u^3). Therefore to minimize ship's hull resistance, hulls of waterjet-driven ships ought to be of a great slenderness – e.g. L/B = 15, stabilized by sponsons, or of semi-swath hydrofoil-supported construction.

Keywords : ship propulsion, hydromechanics, waterjet

INTRODUCTION

Attempts to apply waterjet propulsion to ships have already appeared in the ancient ages[a)]. However the Hamilton's low-power waterjets (1954) intended for propulsion of fast river boats can be considered as the first developed construction[b)]. Nowadays many firms build waterjets of a wide range output : from a few hundred kW to a few dozen MW.

Rolls-Royce, a leader of modern waterjet constructions, offers complete propulsion systems for very fast ferry ships, cargo vessels, warships, cruise ships and yachts.

Up to now about 1400 assemblies of the output from 220 to 70 800 kW have been built. And, a ship propulsion system of 250 MW output is under development

An example of Rolls-Royce waterjet propulsion system for a passenger ferryship is shown in Fig.1.

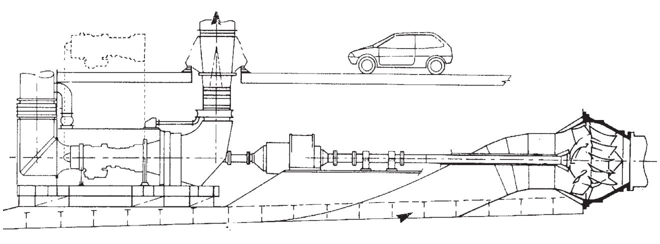

Fig. 1. *ROLLS-ROYCE waterjet propulsion system for a passenger ferryship*

CONSTRUCTIONAL ELEMENTS OF WATERJET PROPULSOR

In Fig.2 the main functional elements of waterjet propulsor are diagramatically presented.

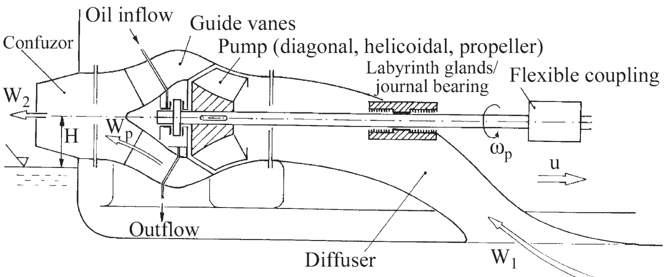

Fig. 2. *Main elements of waterjet propulsor.*
Notation *: w_p – angular velocity of pump; w_1, w_2, w_p – inflow, outflow, and pump flow velocity, respectively; u – ship speed; H – water elevation*

The flow channel consists of a diffuser, rotordynamic pump[c)], guide vanes (stationary) and confusor. The channel surface should be of high smoothness (low coefficient of relative roughness of surface).

The ship manoeuvring devices are shown diagramatically in Fig.3.

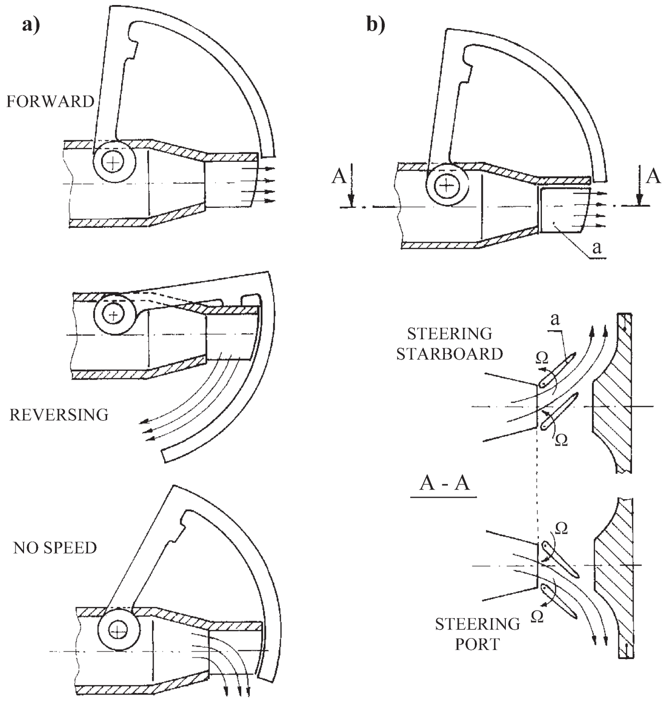

Fig. 3. *Schematic diagram of ship manoeuvring elements:*
a) *for ship reversing;* ***b)*** *for ship turning*
Notation *: a - steering blades, Ω - blade turn angle*

The effectiveness of ship steering is very high because the waterjet force F_u for $u \to 0$ is $F_u(o) \to F_{u,\max}$, and the manoeuvring operations are usually executed at low ship's speed : $u \to o$.

ANALYSIS OF WATERJET PROPULSION EFFICIENCY

By taking into account that the relation :

$$w_1 \cong u \tag{1}$$

is satisfied the absolute values of water velocities at channel inflow and outflow, are :

$$\left.\begin{aligned} c_1 &= w_1 - u \cong 0 \\ c_2 &= w_2 - u \end{aligned}\right\} \tag{2}$$

The force of water stream reaction, is :

$$F_u = m(c_2 - c_1) \cong m(w_2 - u) \tag{3}$$

where : m [kg/s] – rate of water outflow.

For u = o

$$F_u(o) = F_{u,max} \cong m \cdot w_2 \tag{4}$$

Therefore the ship propulsion power is :

$$N_u = F_u \cdot u = m(w_2 - u) \cdot u \tag{5}$$

and carry – over loss output :

$$N_c = m\frac{c_2^2}{2} = m\frac{(w_2 - u)^2}{2} \tag{6}$$

Applying the notation :

N_p – pump propulsion power
η_p – overall pump efficiency
N_L – power of summary flow channel losses

one obtains :

$$N_p \cdot \eta_p = N_u + N_c + N_L \tag{7}$$

The propulsion efficiency η_{N_u} is defined as follows :

$$\eta_{N_u} \overset{df}{=} \frac{N_u}{N_p} \tag{8}$$

hence :

$$\eta_{N_u} = \frac{N_u \cdot \eta_p}{N_u + N_c + N_L} \tag{9}$$

If it is assumed that the efficiency $\eta_p = 1$, then :

$$\eta_{N_u,\eta_p=1} = \eta^o_{N_u} = \frac{N_u}{N_u + N_c + N_L} \tag{10}$$

Inserting (5) and (6) in (10) one obtains

$$\eta^o_{N_u} = \frac{2(1-\bar{u})\cdot\bar{u}}{1-\bar{u}^2 + \frac{2N_L}{m\cdot w_2^2}} = \frac{2(1-\bar{u})\cdot\bar{u}}{1-\bar{u}^2\left(1-2\frac{N_L}{m\cdot u^2}\right)} \tag{11}$$

where : $\bar{u} = \frac{u}{w_2}$ – velocity index.

The expression of relative (nondimensional) losses power :

$$2\frac{N_L}{m\cdot u^2}$$

which may be represented as a sum of *n* particular losses of the waterjet flow in channel, yields the following [5] :

$$2\frac{N_L}{m\cdot u^2} = \sum_{i=1}^{n}\zeta_i \tag{12}$$

Fig.4 shows the diagram of efficiency $\eta^o_{N_u}$ in function of the velocity index :

$$\bar{u} = \frac{u}{w_2}$$

and of the summary losses $\sum\zeta_i$.

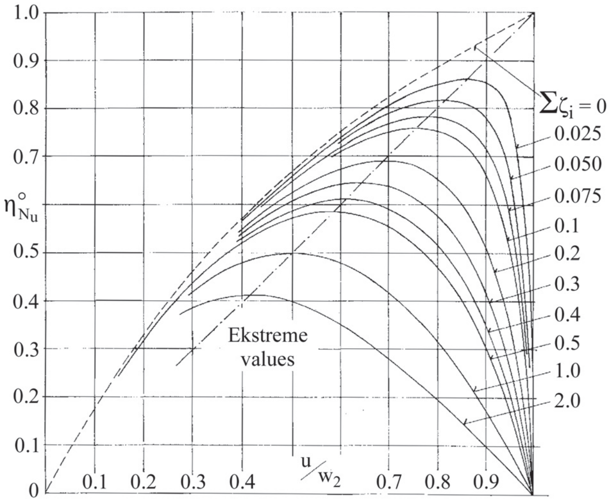

Fig. 4. *Propulsion efficiency* $\eta^o_{N_u}$ *(for* $h_p = 1$*) as a function of* $\bar{u} = \frac{u}{w_2}$ *and* $\Sigma\zeta_i$*, see [3]*

The maximum (optimum) efficiency is the value :

$$\eta^o_{N_u,max} = \eta^o_{N_u}(\bar{u}_{opt})$$

where :

$$\bar{u}_{opt} = \left(1 + \sqrt{\sum_{i=1}^{n}\zeta_i}\right)^{-1} \equiv \eta^o_{N_u,max} \tag{13}$$

In Fig.5 the theoretically determined summary losses (of friction and momentum) are shown :

$$2\frac{N_L}{m\cdot u^2} = \sum_{i=1}^{n}\zeta_i$$

as a function of :

$$\sum_{i=1}^{n}\zeta_i = f(u, H, \bar{u}, \lambda_f) \quad [5] \tag{14}$$

where :

$\lambda_f(Re)$ – the friction number (dependent on the Reynolds number Re, and surface roughness coefficient of the flow channel), are shown for $\bar{u} = 0.8$ and $Re = 10^7$.

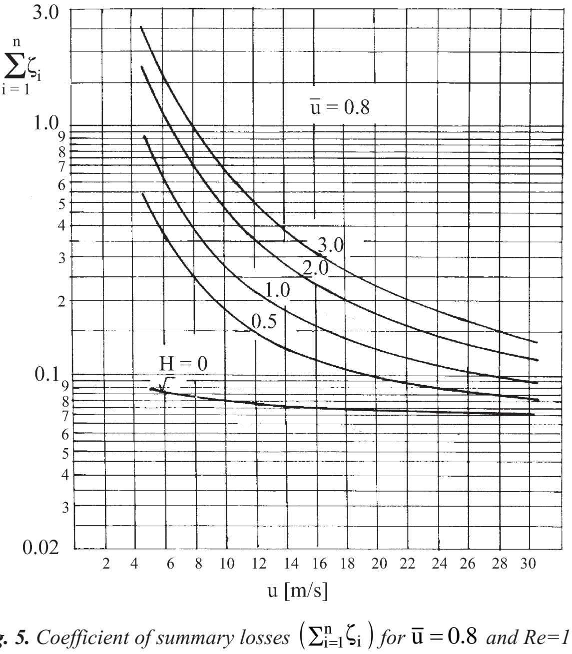

Fig. 5. *Coefficient of summary losses* $\left(\sum_{i=1}^{n}\zeta_i\right)$ *for* $\bar{u} = 0.8$ *and Re=*10^7

In Fig.6 the efficiency $\eta^{o}_{N_u,\max}$ is presented in function of the summary losses $\left(\sum_{i=1}^{n}\zeta_i\right)$

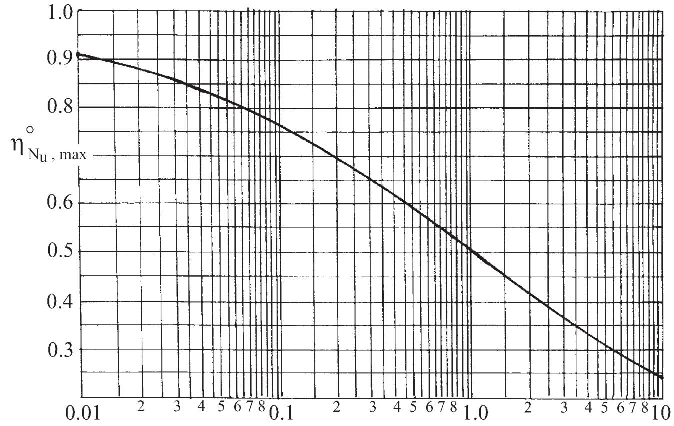

Fig. 6. *The optimum efficiency* $\eta^{o}_{N_u,\max}$ *in function of* $\left(\sum_{i=1}^{n}\zeta_i\right)$

MAIN DIMENSIONS OF WATERJET PROPULSION SYSTEM

The power of ship propulsion is :

$$N_u = m\cdot(w_2 - u)\cdot u = 5402.16\cdot\alpha\cdot u^3 \qquad (15)$$

where :

$$\alpha = \frac{\sqrt[3]{D_w^2}}{C_o}\left[\frac{HP}{kt.^3}\right] \text{ - power coefficient}$$

C_o - Admiralty coefficient

D_W [t] = $\rho_W\cdot V_Z$ - ship mass

$\rho_W = 1.02 \div 1.03$ [t/m^3] - water density

V_Z [m^3] - ship displacement

u [m/s] - ship speed.

Inserting the equation of waterjet flow rate :

$$m = 2\cdot A_2\cdot w_2\cdot\rho_w{}^{d)} \qquad (16)$$

into (15) one obtains :

$$5.3\frac{\alpha}{2A_2}\left(\frac{u}{w_2}\right)^2 + \frac{u}{w_2} - 1 = 0$$

hence :

$$A_2 = 2.65\alpha\frac{\bar{u}^2}{1-\bar{u}} \qquad (17)$$

The graph of the waterjet outflow area of one of both nozzles $A_2 = A_2(\bar{u},\alpha)$ is shown in Fig.7.

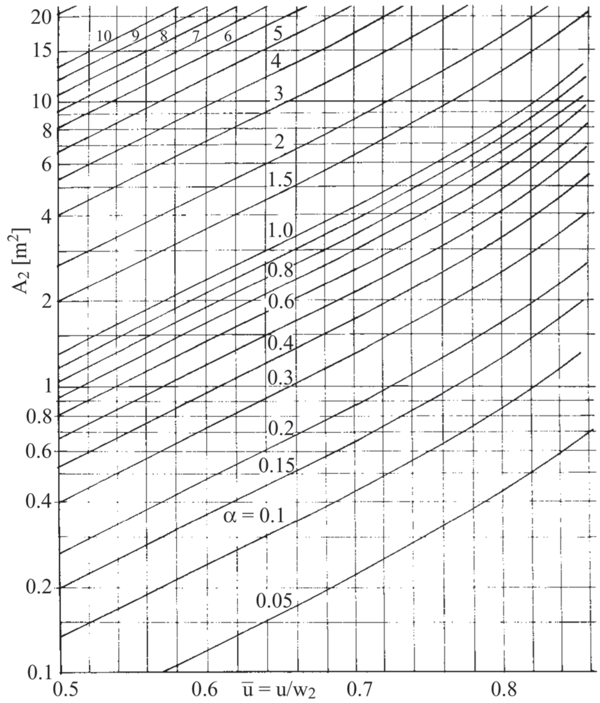

Fig.7. *Waterjet outflow area of one of both nozzles* A_2 *in function of the power coefficient* α *and velocity index* $\bar{u} = \frac{u}{w_2}$

Dimensional proportions of the outflow nozzles are shown in Fig.8 [6].

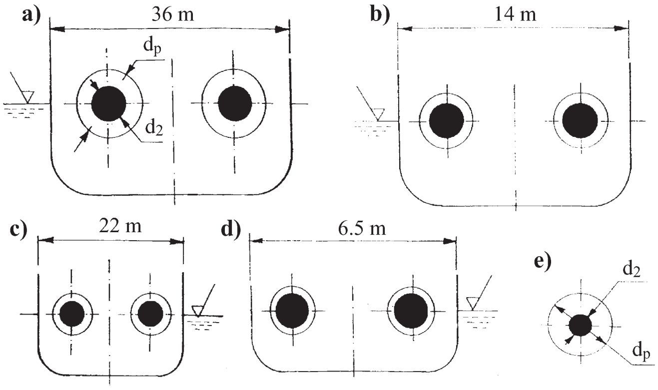

Fig.8. *The stern area of various types of ships (maintaining the dimensional proportions):* ***a)*** *– passenger liner of L = 280 m, u = 12 m/s,* $\alpha = 5.01$ *HP/kt.*^{3}*;* ***b)*** *– passenger vessel of L = 88 m, u = 6 m/s,* $\alpha = 0.907$ *HP/kt.*^{3}*;* ***c)*** *– passenger ship of L = 150 m, u = 9 m/s,* $\alpha = 2.23$ *HP/kt.*^{3}*;* ***d)*** *– tug of L = 40 m, u = 5.6 m/s,* $\alpha = 0.207$ *HP/kt.*^{3}*;* ***e)*** *– racing boat of u = 25 m/s*

AN EXAMPLE ARRANGEMENT OF THE SHIP WATERJET PROPULSION SYSTEM WITH GAS-TURBINE DRIVE

The considered waterjet system is intended for a passenger ship of the following parameters :

ship length L = 80 m, L/B = 6.3 , ship mass D_W = 4000 t, speed u = 6 m/s (11.7 kt.), Admiralty coefficient C_o = 300, power output $N_u \cong 980$ kW, having main engine : one-cylinder gas turbine with heat exchange regeneration (air preheater), of effective efficiency :

$$\eta_e^{GT} = 0.33 \div 0.34$$

Assuming the velocity index $\bar{u} = \frac{u}{w_2} = 0.75$ and taking into account the power coefficient

$$\alpha = \frac{1}{C_o}\sqrt[3]{D_w^2} \cong 0.84$$

one gets from the diagram in Fig.7 : $A_2 \cong 5$ m^2 hence, the outflow diameter is: $d_2 \cong 1.8$ m.

If H = 0 , $\eta_p = 0.9$ and $\left(\sum_{i=1}^{n}\zeta_i\right) = 0.085$ is assumed (Fig.5), then :

$$\eta^{o}_{N_u,\max} = \frac{1}{1+\sqrt{\sum_{i=1}^{n}\zeta_i}} = 0.774$$

hence :

$$\eta_{N_u} = \eta^{o}_{N_u}\cdot\eta_p = 0.696$$

The effective power of the gas turbine is :

$$N_e^{GT} = \frac{N_u}{\eta_{N_u}} \cong 1400 \text{ kW}$$

The waterjet propulsion system with gas turbine, located in the stern part of the ship, is shown in Fig.9.

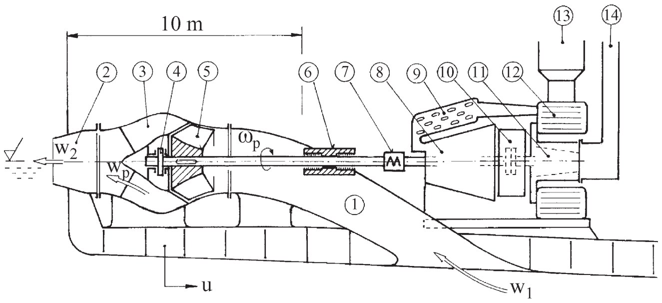

Fig.9. *The waterjet propulsion system located in the ship's stern part: 1 - diffuser; 2 - confusor (outflow nozzle); 3 - guide vanes; 4 - thrust & journal bearing; 5 – diagonal-helical pump; 6 - labyrinth gland/journal bearing; 7 - highly flexible coupling; 8 - gas turbine; 9 - combustion chamber; 10 - gear box; 11 - axial–radial compressor; 12 - recovery heat exchanger (air preheater); 13 - exhaust gas duct; 14 - air inflow duct*

The driving gas turbine with regeneration heat exchanger, is shown diagramatically in Fig.10.

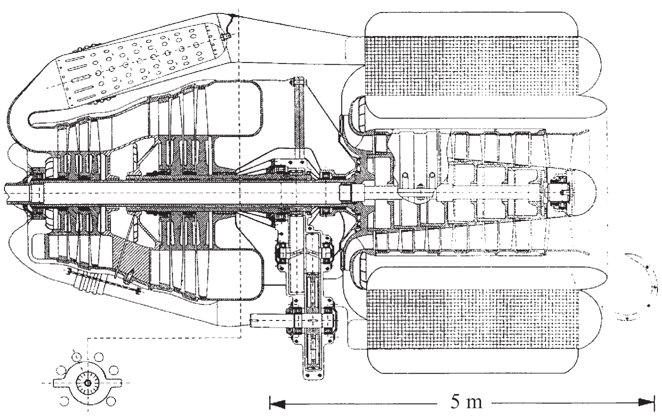

Fig.10. *Longitudinal cross section of a gas turbine with regeneration heat exchanger (suitably shaped and located)*

If the ship's hull is very slender, e.g. of L/B = 15, and stabilized by two pairs of the slim sponsons (s) – see Fig.11, the ship will develop the speed up to 8 m/s (15.55 kt.), at the same output of main engine.

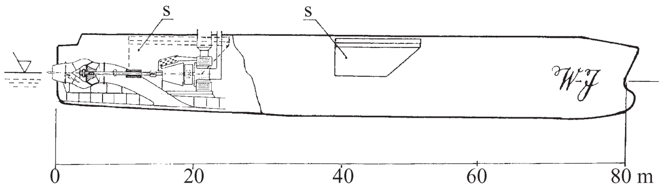

Fig.11. *Profile of a very slender ship (L/B = 15) propelled by a gas turbine waterjet system*

FINAL REMARKS

- The waterjet propulsion system has some essential advantages in comparison with that conventional based on screw propellers :
  - absence of any rotational elements behind the hull
  - smaller losses due to wake current (of about 13% ÷ ÷ 19% [2])
  - favourable efficiency index at partial loads
  - torsional vibration diminution
  - effective ship turning and reversing
  - possible elimination of rudder blade, resulting in a lower hull resistance.
- Summary losses are inversely proportional to u^2, and monotonically decreasing with the ship speed u increasing. They are very weakly dependent on the velocity index $\bar{u}$.
- The great dimensions of flow channel are a serious problem of waterjet arrangement. The outflow area A_2 is functionally dependent as follows :

$$A_2 \infty \alpha \left(\frac{\bar{u}^2}{1-\bar{u}} \right)$$

where : α, acc. to eq.(15), is a coefficient dependent on dynamic ship hull properties, whereas the expression $\left(\frac{\bar{u}^2}{1-\bar{u}} \right)$ is directly proportional to the propulsion efficiency, which means that the greater the propulsion efficiency, the greater the nozzle dimensions (!).

- The following problems are important for improving construction of waterjets :
  - smoothness maintenance
  - the pump and flow channel protection against accidentally flowing-in hard pieces
  - development of automatic control elements for ship turning and reversing
  - development of construction of journal & thrust bearing situated inside pump, e.g. a ceramic bearing with water-film lubrication.

NOMENCLATURE

B	- ship breadth
c_1 , c_2	- relative water speed at inflow and outflow, respectively
d_p	- diameter of pump outflow
d_2	- diameter of confusor outflow
F_u	- propulsion force
H	- waterjet height in relation to sea level
HP	- horsepower
kt	- knots
L	- ship length
m	- flow rate
N_c	- carry-over loss output
N_u	- ship propulsion power
u	- ship speed
w_1 , w_2	- inflow and outflow water velocity, respectively
ξ_i	- nondimensional loss of i-th component

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[a] Archimedes axial water pump (287-212 AChN), Leonardo da Vinci pump (1452-1519), Toogwood's & Hayese's patent (1661), Beniamin Franklin's pulsators (1706-1790)

[b] So-called „First Hamiltonians"

[c] The pump may be of various type: diagonal, helicoidal or propeller pump

[d] Water flow rate of two waterjet nozzles