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Examination of the fuel supply system of a naval gas turbine in operation

SUMMARY

Preliminary results are presented of fuel consumption measurements in a naval multi-shaft gas turbine. The main aim of the examination was to evaluate the relationship between fuel mass flow and pressure drop at two-passage fuel injectors. The results are used to verify values of the fuel outflow coefficient applied to an injector mathematical model, as well as to check a method, under development, for diagnosing the fuel supply system of the engine in service conditions.

INTRODUCTION

The main task of the fuel supply system of the gas turbine is to provide an appropriate fuel flow to the combustion chamber. For reliability reasons the fuel injectors take a special place within the installation, apart from turbine design.They ensure high efficiency of combustion process of the fuel by spraying it into suffciently small drops in advance. In result, an aerosol is made consisting of droplets of 10÷20 μm diameter [4,5]. Such fuel comminution makes complete vaporization of the aerosol and effective combustion of it during flow through combustion chamber possible. The greater droplet dispersion the shorter the time necessary to vaporize them and form homogeneous air-fuel mixture, which inertia of the combustion process depends on.

Some disturbances of correct injector performance can appear during operation of the engine at sea conditions. They result from the continuous fouling and wearing process of the injector flow passages as well as from diverting characteristics of ageing control elements [2]. In consequence, the flow rate, spraying quality and geometry of fuel flow out of the injector changes. Also, unfavourable deformations of the temperature field distrubution within exhaust gas flow behind the combustion chamber occur, which can cause local overheating of its structural elements. Turbine units are also exposed to failure, especially their guide vanes under high thermogasodynamic loading due to irregular working medium flow.

Technical state of the injectors should be periodically checked to avoid possible engine failures and worsening their performance effectiveness. Dismantling-free control methods are more and more popular as they are possible to be used at ship operation conditions. Measurements of fuel flow rate, apart from the selected thermogasodynamic parameters which characterize engine load, can be an important source of diagnostic information on technical state of the fuel supply system [1,6].

CALCULATION MODEL OF THE INJECTOR

The two-passage turbulent injectors schematically depicted in Fig.1 are commonly applied to naval gas turbines. They ensure high fuel spraying effectiveness within the entire range of engine load changes.

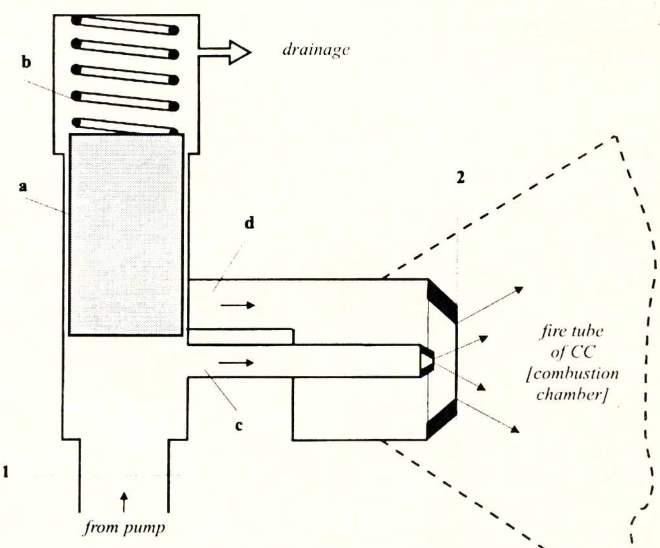

Fig. 1. Scheme of fuel flow through the two-passage turbulent injector
a – fuel distributor, b – spring, c – I injector passage,
d – II injector passage, 1, 2 – control cross-sections

The first injector passage with the sprayer of the smaller hose diameter operates at low engine loading, i.e. from idle running to about 0.1÷0.2 rated power (P_{nom}). It corresponds to fuel pressure changes in the main from 0.7 to 2.5 MPa. Along with increasing the engine rotational speed, and thus the fuel pressure, the distributor plunger goes up opening the second injector passage with the sprayer of the greater hose diameter. A time instant of opening the second passage is determined by distributor spring characteristics. When the pressure increases to about 3.2÷3.5 MPa the full active cross-section area of the second flow passage becomes opened. Fuel is supplied to the engine through both the injector passages working together.

The flow continuity equation is commonly used for mathematical description of the gas turbine injector in steady state operation. It makes possible to determine the mass flow rate of the fuel pumped through injector passages, considered as the ideal fluid, in compliance with the following formula :

$$\dot{m}_w = \mu_{wyp}\, A_{wyp}\, \rho_{(T)}\, w_{wyp} \tag{1}$$

where :

μ_{wyp} - fuel outflow coefficient
A_{wyp} - sprayer hose cross-section area in the fuel outflow plane
$\rho_{(T)}$ - fuel density determined for the fuel temperature at the fuel outflow plane
w_{wyp} - velocity of the fuel flow out of the sprayer hose.

The relationship between the flow velocity and static pressure in steady state flow of the ideal fluid is determined by Bernoulli equation as follows :

$$p_1 + \frac{\rho . w_1^2}{2} = p_2 + \frac{\rho . w_2^2}{2} = idem \tag{2}$$

where :

p_1 , w_1 - fuel flow pressure and velocity in the fuel pipe just in front of the injector, respectively
p_2 , w_2 - pressure in the combustion chamber and velocity of the fuel flow out of the sprayer hose, respectively
ρ - fuel density.

The flow velocity w_1 in the fuel pipe in front of the injector does not exceed 5÷8 m/s [4] and is many times lower than that of the fuel flow out of the sprayer hose, w_2 . Therefore the dynamic pressure component on the left hand side of the expression (2) can be omitted and the expression for the velocity of the fuel flow out of the sprayer hose can be written as follows :

$$w_{wyp} = w_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho}} \tag{3}$$

Finally, the mass rate of the fuel flow into the combustion chamber can be determined from the following relationship :

$$\dot{m}_{pal} = \sqrt{2\rho_{(T)}\Delta p_w}\left[\sum_{k=1}^{n}(\mu_{wyp}\, A_{wyp})_k\right] \tag{4}$$

where :

k - number of injectors
$\Delta p_w = p_1 - p_2$ - pressure drop in the injectors.

Determination of the fuel outflow coefficient μ_{wyp} for a particular injector is especially difficult during evaluation of the mass rate of the fuel inflow to the combustion chamber of the engine in operation. It functionally depends on the flow character defined by Reynold's number and on shape and dimensions of the sprayer hose [4]. For this reason it is usually determined experimentally. For the injector in question the value of the coefficient $\mu_{wyp} = 0.92 \pm 0.02$ was specified by its manufacturer as obtained at the test stand in „the cold combustion chamber" [4]. The value should be considered as a preliminary estimate only. In real operation conditions of the injector installed in the engine, its elements directly influenced by fuel combustion zone are heated up to high temperature values (of 500÷600 K). The flow passages become „deformed" thus determining a new, real value of the fuel outflow coefficient. Another operational and production problem is the necessity of selecting the injectors for each engine on the basis of similar mass flow rate values of the first and second flow passage. Manufacturing unrepeatability of the injectors used in the engines on the Polish Navy vessels is the cause of a large scatter of the fuel flow rate, ranging up to 5÷7% in one engine set [5].

AIM OF THE INVESTIGATIONS, MEASUREMENT DEVICES

The experimental investigations were carried out on an engine of DR76 type, operating in COGAG propulsion system of a fast vessel. They were aimed at determining the mean value of the fuel outflow coefficient of the injector set installed in the engine, as well as at determining mutual relationship between the fuel mass flow rate in the engine and injector pressure drop. Such experimentally acquired information can be used to verify a mathematical model of the engine fuel supply system as well as a simulation model of the system, being under development for diagnostic purposes.

To reach the aim it was necessary to apply devices for measuring and recording the fuel consumption of the naval gas turbine in various states of loading. Therefore the LS5376 high accuracy flowmeter made by OVAL ENGINEERING Co. Ltd was used. Main technical particulars of the flowmeter are presented in the table below.

Main technical particulars of the applied LS5376 flowmeter

Nominal diameter	Measurement range	Pressure drop at max. flow	Max. working pressure	Measurement accuracy
mm	dm^3/h	MPa	MPa	%
40	150÷4000	0.013	1.0	±0.5

In the investigations DIAGNOZER 3 , the Computerized Measuring & Recording System [3] was applied which made it possible to simultaneously measure [6] :

⇒ fuel pressure and temperature at the first injector passage
⇒ rotational speeds of the engine rotor units
⇒ air pressure behind the low pressure compressor (LPC) and high pressure compressor (HPC) as well as
⇒ air pressure and temperature at the engine inlet cross-section.

COURSE OF THE EXPERIMENTAL INVESTIGATIONS AND THEIR RESULTS

Recording the engine operation parameters was carried out at the following engine loads : 0.2, 0.4, 0.6, 0.8 and 1.0 P_{nom} . At each load level the volumetric fuel flow rate was measured for 60 s in four measurement series. On this basis, values of the fuel mass supplied to the combustion chamber and of the mean outflow coefficient of the injectors were calculated. To perform the calculations it was necessary to determine the mean area of the injector hose cross-section at the fuel outflow plane. The two-passage injector of „W" series, no. 2446, used in DR76 engines was selected for the measurements. Values of the cross-section diameters of the injector outlet passages were measured by means of a microscope. The following results were obtained :

- at I flow passage : D = 0.19 mm
- at II flow passage : D = 1.48 mm

In result, courses of the working parameters of the engine fuel supply system, shown in Fig.2,3 and 4, were obtained.

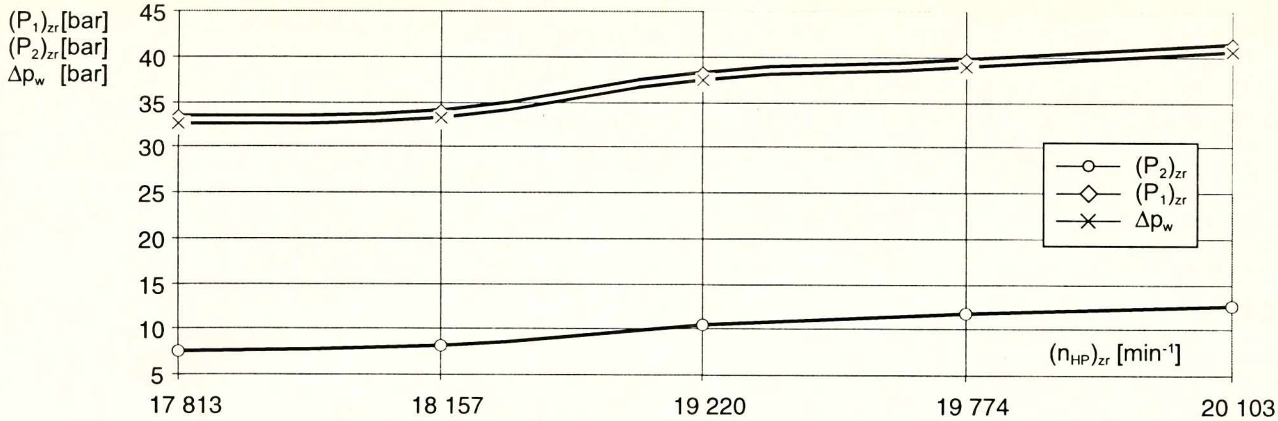

Fig.2. Changes of the fuel flow pressure $(P_1)_{zr}$, pressure in the combustion chamber $(P_2)_{zr}$ and pressure drop within the injectors Δp_w in function of HP rotor speed

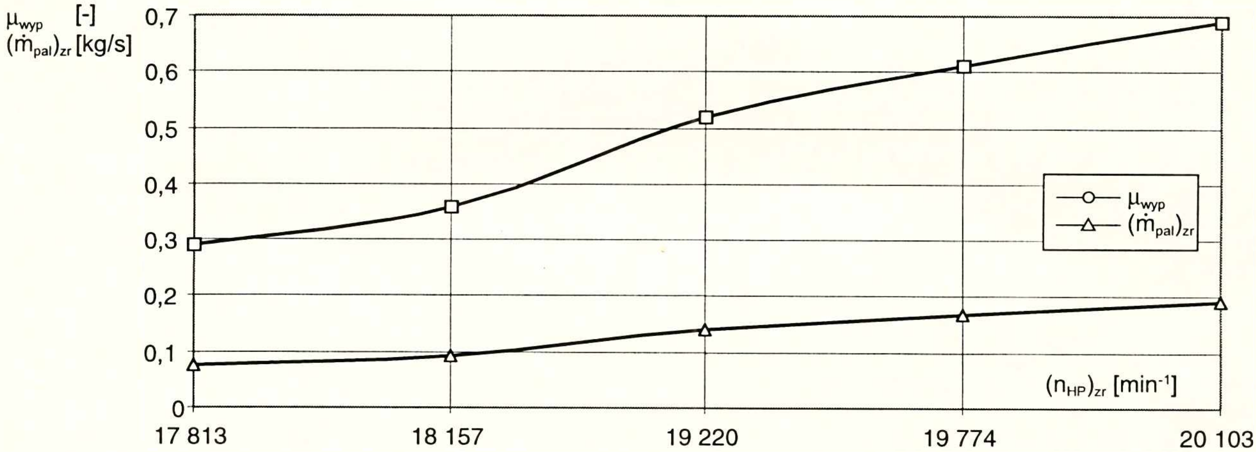

Fig.3. Changes of the fuel mass flow rate $(\dot{m}_{pal})_{zr}$ and mean fuel outflow coefficient μ_{wyp} in function of HP rotor speed

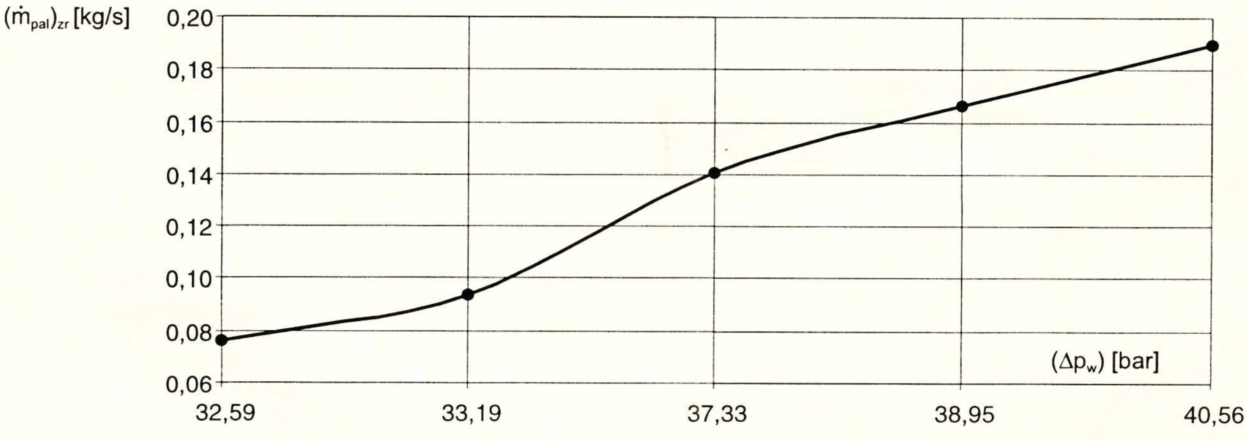

Fig.4. Relationship between the fuel mass flow rate $(\dot{m}_{pal})_{zr}$ and pressure drop within the injectors Δp_w

The obtained results (presented in Fig.2 and 3) make it possible to determine the correlation between the parameters characterizing operation of the engine supply system in steady working states. Moreover, on the basis of the results shown in Fig.4 determination of the fuel flow rate over the entire loading range becomes possible. On the basis of Fig.3 it can be stated that the values of the fuel outflow coefficient, experimentally determined for the investigated injectors, are highly changeable with the engine loading changes. In the investigated ranges of steady operation of the engine, values of the fuel outflow coefficient are far lower than those specified by the injector producer, not exceeding μ_{wyp}= 0.7.

From the presented courses it can be sean that values of all analyzed parameters strongly increase over the engine partial load range, i.e. about 0.4 to 0.6 P_{nom}. This character of the course changes is connected with the commencing operation of the second passage of the injectors.

The values of so determined fuel outflow coefficient, related to the HP rotor speed changes can be compared with the standard ones, recorded at the beginning of engine exploitation.

They form then a generalized symptom of the technical state of the flow passages of the injector set of the engine in routine operation.

CONCLUSIONS

- The obtained results of the fuel consumption investigations, for the first time carried out directly on the engine operating during sea manoeuvres of the vessel, form the basis for verification of the technical characteristics provided by the manufacturer. Also, they serve as an introduction to the deeper analysis of the problem, i.e. the adequacy assessment of the mathematical model of the fuel supply system of DR76 engine, under development for diagnostic purposes.
- The proposed experimental method of determining values of the generalized (mean) fuel outflow coefficient for an applied turbulent injector set makes it possible to estimate the fuel mass flow to the combustion chamber of the gas turbine operating in steady states, merely on the basis of measurements of the fuel temperature and of pressure drop within the injectors. It was aimed at demonstration of a possible way of estimating the fuel consumption by the engine with the use of the ship control-measurement system. Thus, it becomes unnecessary to apply a flowmeter to assess the technical state of the engines. This is an important advantage with a view of the safety during carrying out the diagnostic investigations in ship operation conditions.
- The established mutual relationship between the pressure drop within the injectors and fuel mass flow rate forms, together with the assumed reference value of the fuel outflow coefficient, the diagnostic parameter for the assessment of technical state of the fuel supply system, an essential contribution to the developed method of diagnosing the naval gas turbines in operation.

NOMENCLATURE

A_{wyp} - sprayer hose cross-section area in the fuel outflow plane
D - cross-section diameter of the injector outlet passages
k - number of injectors
$\dot{m}_{pal}$ - mass rate of the fuel into the combustion chamber
$\dot{m}_w$ - mass flow rate of the fuel pumped through injector passages
n_{HP} - rotational speed of the engine high pressure rotor unit
P_{nom} - engine rated power
p_1, w_1 - fuel flow pressure and velocity in the fuel pipe just in front of the injector, respectively
p_2, w_2 - pressure in the combustion chamber and velocity of the fuel flow out of the sprayer hose, respectively
w_{wyp} - velocity of the fuel flow out of the sprayer hose
zr - index of reduced value
Δp_w - pressure drop in the injectors
μ_{wyp} - fuel outflow coefficient
ρ - fuel density
$\rho_{(T)}$ - fuel density determined for the fuel temperature at the fuel outflow plane

Appraised by Adam Charchalis, Prof.,D.Sc.,M.E.

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Conference

An interesting conference

Health care of seamen and other maritime economy workers is not often a theme of the scientific meetings of the physicians together with designers, builders and operators of ships and port facilities. Therefore the conference held in November 1998 should be specially noticed. It was organized by the Institute of Port and Fleet Exploitation, Maritime University of Szczecin and Working Condition Inspection of Szczecin District, under the heading :

Protection of the man working in the marine environment against its hazards

During the conference 14 papers were read, 9 out of which dealt with the following **technical and organizational problems** :

- „International activity for improving the safety at sea and protection of marine environment" (by L.Plewiński of Maritime University, Szczecin)
- „Cooperation scheme of a passenger ship with SAR centres versus safety at sea" (by P.Wołejsza of Maritime University, Szczecin)
- „Modern methods of shipborne noise investigation" (by S.Weyna of Technical University of Szczecin)
- „Analysis of the accidents occurred in the ports of Szczecin, Świnoujście and Kołobrzeg" (by Z.Jóźwiak of Maritime University, Szczecin)
- „Safety problems in operating of the port dry cargo cranes" (by K.Górnicki of Maritime University, Szczecin)
- „An underwater system for identification of dangerous objects - elimination of hazards to divers" (by T.Graczyk and D. Zawada-Michułka of Technical University of Szczecin)
- „Monitoring the state of the chemical ammunition (war toxic means) sunken in the Baltic Sea and its influence on marine environment" (by T.Kasperek)
- „Influence of pollution by oil products on the engine room crews" (by J.M.Grudziński of Maritime University, Szczecin)
- „Testing methods of the safety-protecting clothing used in maritime economy with a view of the required certification of it" (by K. Łężak)

and 5 of the papers were devoted to **medical problems** :

- „Preventive activity of The State Inspection of Working Conditions in the area of maritime economy" (by T.Sułkowski, Inspector in Chief)
- „Preliminary medical cause analysis of the Polish Shipping Company seamen retirements to the disability rents" (by A.Kosińska, A.Szlarb, J.Ilecki of the Port Public Health Centre of Szczecin)
- „Muscular-skeleton ailments occurring in seamen" (by R.Paluch and A.Wandycz)
- „Onboard heart attacks qualified as work accidents" (by A.Szlarb of the Port Public Health Centre of Szczecin)
- „Influence of onboard working conditions on abnormal weight growth and its relation to artery hypertension occurrence in seamen" (by H.Trawińska-Dyrdał of the Port Public Health Centre of Szczecin)

After disscussion in the topic groups, completed with conclusions the Conference's participants were given the opportunity of taking part in an attractive, 4-day excursion to Malmö and Copenhagen by a ferryship.