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IMPACT OF PRESSURE DROP IN COMBUSTION CHAMBER ON GAS TURBINE PERFORMANCE

Jerzy **Herdzik** [1]

[1] Gdynia Maritime University, Faculty of Marine Engineering, Department of Marine Propulsion Plant, Morska 81/87, 81-225 Gdynia, Poland, email: j.herdzik@wm.umg.edu.pl, https://orcid.org/0000-0002-2339-807X

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Abstract – Paper discusses the problem of pressure drop in the process of working medium flow through combustion chamber of gas turbine. The pressure loss is an internal disadvantage of combustion chamber depends on many parameters, especially the chamber design and working gas flowrate. There is a problem to calculate the parameters of working medium in characteristic points of gas turbine thermodynamic cycle because the total pressure before and after combustion chamber is not known. There is a lack of information from manufacturer about it and in publications as well (mainly no experimental data, only theoretical considerations). It will be important information because the pressure drop has an meaningful influence on gas turbine performance. The paper presents an estimation of decreasing the performance of gas turbine from discussed reason. Author of that manuscript recognized the necessity of showing the importance of that parameter and turning the attention to not fully recognized problem.[1]

Key words – gas turbine, gas turbine performance, impact on performance, pressure drop measurement

JEL Classification – R49, Q49, Q56, Q59

INTRODUCTION

Combustion in gas turbine, working in open cycle, is a continuous process in which fuel burned after mixing with the air supplied by the compressor. The principle requirements for a combustion chamber are [1-2]:

- low weight and small frontal area;
- low pressure loss;
- stable and efficient combustion regardless of load and over a large range of air/fuel ratio;
- outlet temperature stability (turbine inlet temperature TIT);
- reliability, serviceability and reasonable life, etc.

It is commonly known that increased pressure drop during the flow through combustion chamber considerably reduces turbine output and efficiency. Compressed air flows to combustion chamber in two or three principal paths arranged in parallel. The pressure drop in paths have an influence on the air flowrate and vice versa. The division of air between the paths is determined by their relative resistances and must be the same. In such condition the division of flowrate is proportional to cross section area of the paths. A schematic drawing of combustion chamber is presented in Fig. 1. It was shown points for the measure of differential pressure – a pressure drop in combustion chamber. When we divided the pressure drop through pressure at inlet to combustion chamber we receive a specific pressure drop. Since the overall air/fuel ratio is in a range 60÷200:1, while the stoichiometric is about 15:1, the air should be delivered in stages. The temperature in primary zone can reach over 1900°C, far higher than the most materials can withstand. A part of the air from compressor may be used to cool the walls of the combustion chamber liner. Only about 10÷30% of air flowrate takes a contribution directly in combustion process inside the primary zone. About 30÷40% is used as secondary air for complete the combustion and decreasing the temperature of combustion chamber on outside surface and about 20÷30%

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goes in dilution zone for mixing and dilution the exhaust gases to turbine inlet temperature (TIT or T_3). About 5÷30% of air flow bypasses combustion chamber and goes for cooling purposes of turbine blades in the first and second stage [3]. There is more often about 8÷30 annular combustion chambers for one gas turbine. The separate flame tubes are interconnected.

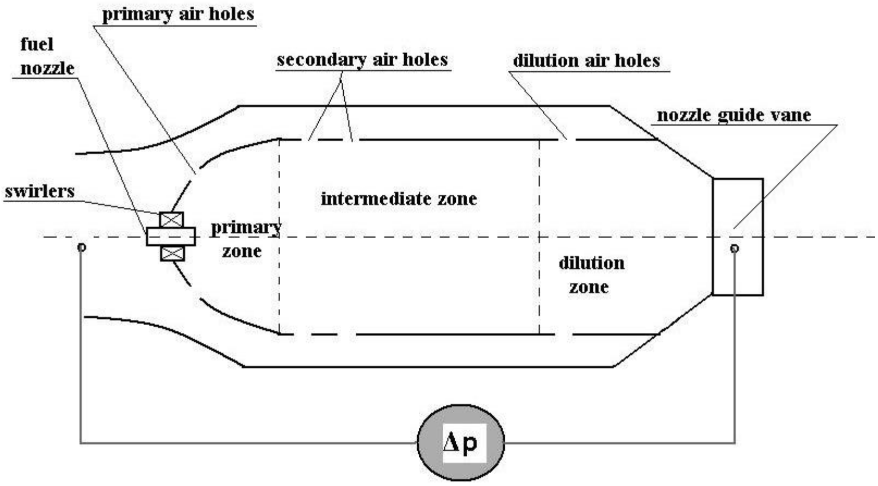

Fig. 1. Schematic drawing of combustion chamber [own drawing]

1. MEASUREMENT PROBLEMS WITH PRESSURE DROP IN COMBUSTION CHAMBER

There is a big uncertainty of pressure drop in combustion chambers because the gas turbine producers did not inform about it. Of course, the pressure drop depends on turbine load and air flowrate, but even for nominal load there are no data. At the same time, there is only a small quantity of reports from researchers presenting results of measurement.

Total pressure drop consists of component losses as following:

- pressure drop due to a swirler;
- primary stabilizer losses;
- cooling losses;
- mixing losses;
- heat addition losses;
- other miscellaneous losses due to friction, diffusion etc.

After some simplifications, it is possible to divide the total pressure drop on static and dynamic drop [4]. A measure of static pressure drop (Δp_s) is easier. It should have a possibility to implement an access to two channels before and after combustion chamber (Fig. 1). For computing the dynamic pressure drop (and as a sum the total pressure drop) it should be known the density and velocity of gases before and after combustion chamber (in the same points for static drop measurement). It is possible to compute when it was delimited through a measurement of temperatures, mass flows and cross section areas in mentioned points.

There are quite a few theoretical methods for calculating pressure drop in combustion chamber, especially important possibility for partially loads of gas turbine.

Popular methods are based on an assumption that total pressure drop is a sum of only two components: pressure loss caused by a friction during isothermic flow through combustion chamber and pressure loss caused by increasing the specific volume of the flowing gas as a result of temperature change (heating). The others are based on directly computing the pressure drop as a result of thermodynamic parameters change [5÷7].

For example one of the proposition is that combustion chamber pressure loss is a sum of two distinct causes:

- cold loss (skin friction and turbulence) – stable, depends only on air flow;
- hot loss (the rise temperature due to combustion) – depends on the turbine load.

The estimation of pressure loss is possible analytically: the cold loss can be predicted with the aid of the Fanno-line functions, the hot loss with the aid of Rayleigh-line functions [7÷10].

The proper measurement of combustion chamber pressure loss makes a lot of difficulties due to high temperatures and turbulent flow (the value of pressure is not the same in the area of cross section). Pressure loss changes with the turbine load and may be differentiated due to some imperfections or failures of combustion process [11÷14].

Pressure loss strongly depends on the construction of combustion chamber (mainly the area of cross sections), the change of flow direction, the process of air swirling and mixing exhaust gases with air, etc. Because these processes are independent to the operator the gas turbine producers did not inform about it. It is an internal affair of manufacturers and like a black box for the operator.

2. THEORETICAL IMPACT OF PRESSURE DROP IN COMBUSTION CHAMBER ON GAS TURBINES PERFORMANCE

The possible performance for MT30 gas turbine was presented in Fig. 2 in two configurations: as theoretical without pressure losses with isentropic compression and expansion, and as with standard inlet and outlet losses with polytropic compression and expansion.

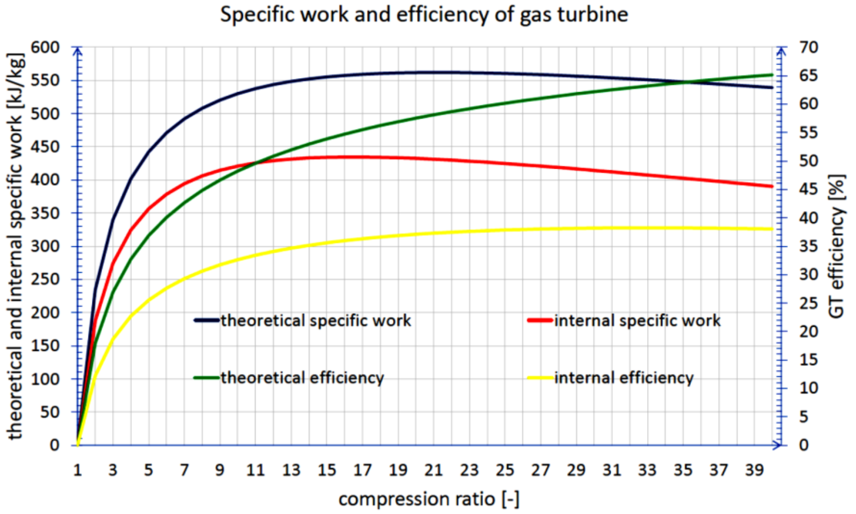

Fig. 2. Theoretical and internal specific work and efficiency of MT30 for ISO parameters in dependence of compression ratio (**combustion pressure loss is zero**) [own graph]

The basic parameters of Rolls Royce marine gas turbine MT30 were presented in Tab. 1 [15]. It has worked as prime mover on a vessel and has driven the fixed pitch propeller (through clutch, gear box and shaft lines).

During calculations and estimation it was used following data:

- specific heat of air at constant pressure = 1.005 kJ/kgK;
- specific heat of exhaust gases = 1.1 kJ/kgK;
- mass airflow = 115 kg/s;
- coefficient of compression = 0.2857;
- coefficient of expansion = 0.2537;
- ambient pressure = 100 000 Pa;
- ambient temperature = 288.15 K (15^{o}C);
- relative air humidity 60% (ISO standard conditions [16]);
- temperature inlet to turbine at nominal power TIT = 1653 K;
- installation pressure losses: at inlet 981 Pa and at outlet 1472 Pa;
- elevation of gas turbine = 0 m (sea level);
- combustion chamber efficiency =1;
- pressure drop in combustion chamber = 0 (before estimation);
- nominal compression ratio = 20;
- polytropic (internal) efficiency of compressor = 0.90;
- polytropic (internal) efficiency of turbine = 0.89;
- molecular coefficient change of working medium = 1.015;
- specific fuel consumption at nominal power 0.22 kg/kWh;
- low heat value of fuel (marine diesel oil) = 42707 kJ/kg.

Table 1. Basic parameters of MT 30 gas turbine

Parameter	Unit	Value
Nominal power	MW	36
Maximal power (limited)	MW	40
Idling speed	rpm	920
Nominal rotational speed	rpm	3300
Maximal rotational speed	rpm	3418
Over speed trip	rpm	3600
Compression ratio (nominal)	-	20
Nominal inlet temperature to turbine	°C	1380
Inlet flow (nominal)	kg/s	115
Exhaust flow (nominal)	kg/s	117
Exhaust temperature (nominal)	°C	395
Specific fuel consumption (diesel oil)	kg/kWh	0.220

The nominal pressure ratio of GT depends on its basic parameters and should be choose between the pressure ratio when the specific work reaches maximum and the pressure ratio when the GT efficiency reaches maximum (see Fig. 3). For that turbine the nominal pressure ratio amounts 20.

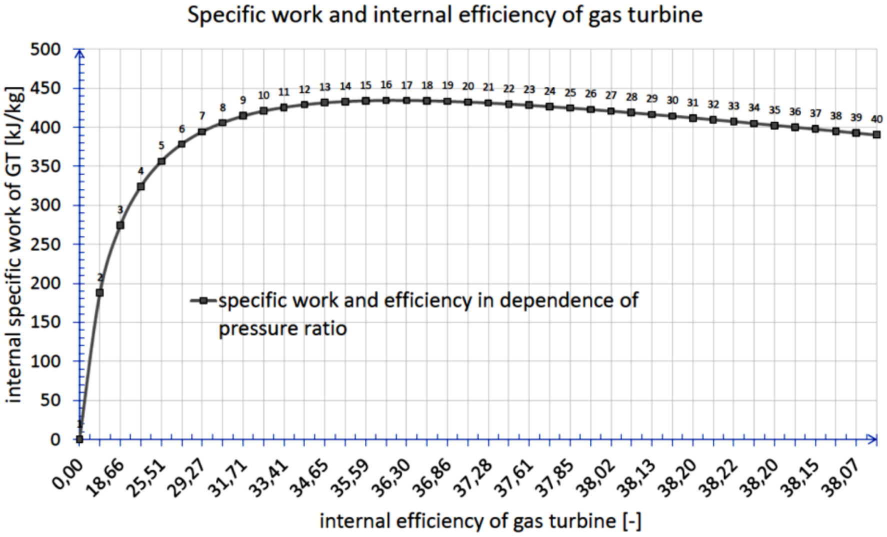

Fig. 3. Internal specific work and efficiency of MT30 for ISO parameters in dependence of compression ratio [own graph]

The accessible power of gas turbines depends on many conditions, for example the installation effects especially on pressure losses in inlet duct, in combustion chamber and exhaust gases outlet. For MT30 it is accepted the 4 inch (100 mm) of water gauge (w.g.) of nominal inlet loss and 6 inch (150 mm) of nominal exhaust loss [15-16]. If the pressure drop increases to 400 mm w.g.:

- on inlet side decreases the power about 5% and increases the SFC about 0.9%;
- on exhaust side decreases the power about 1.7% and increases the SFC about 1.1%.

An example of indicative effect of installation pressure losses of MT 30 on power and specific fuel consumption is presented in the Fig. 4 [15].

It was done an estimation for basic parameters of MT30 as a representant of contemporary GT family. The Fig. 5 presents the dependence of specific work and efficiency of GT on temperature inlet to turbine (GT load) where the combustion pressure loss is zero at standard ISO conditions in dependence of turbine inlet temperature (TIT, T_3). It may be seen that temperature T_3 (TIT) has an significant influence on GT parameters. At idling load of GT the parameters (for analyzed turbine at about 680°C or 930K) the net work ratio of GT decreased to zero. In the other hand because the temperature T_3 is limited (here is 1380°C) the specific work and efficiency reach levels about 430 kJ/kg and 38.3% accordingly. These parameters, the most important for GT performance, may rise if temperature TIT will increase over limited zone.

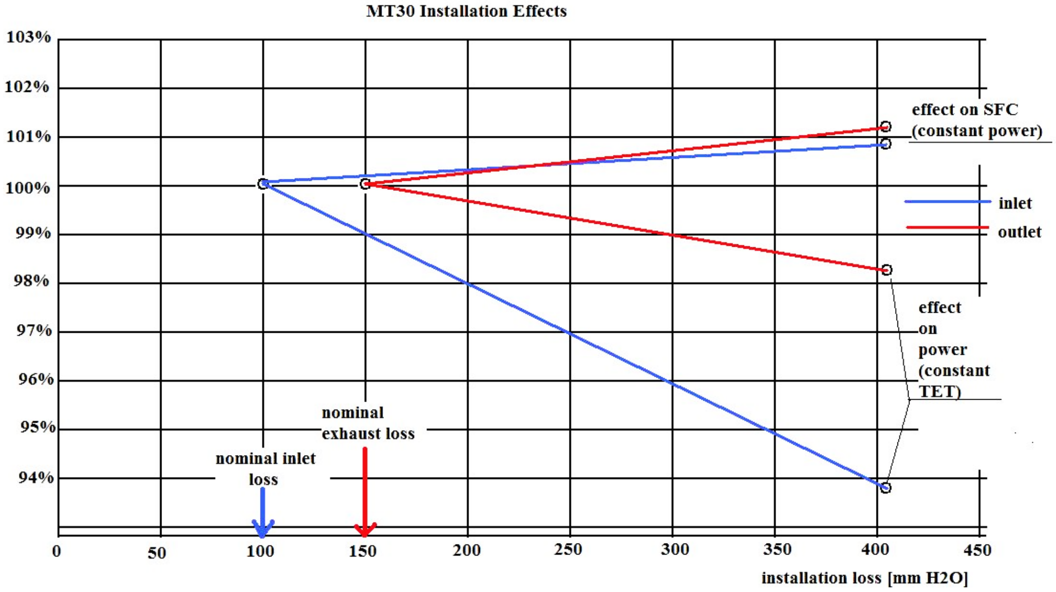

Fig. 4. Indicative effect of installation pressure loss on SFC and power of MT30 gas turbine [own graph]

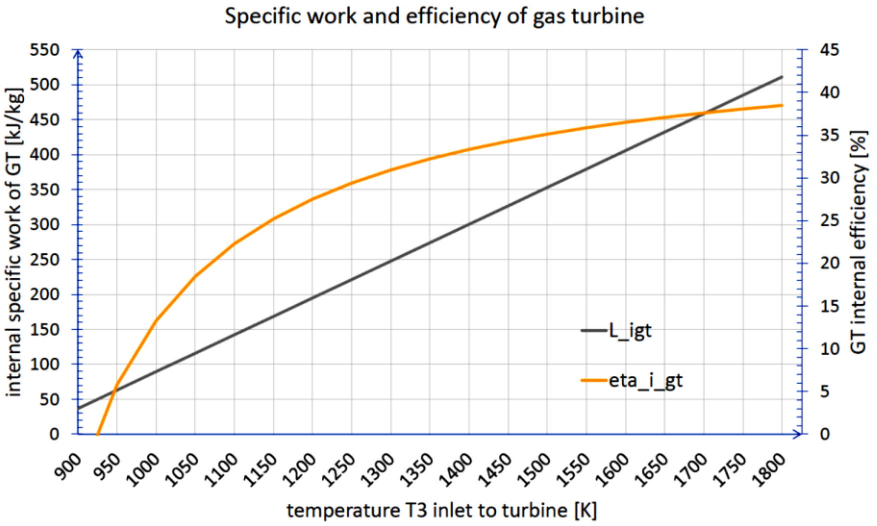

Fig. 5. Specific work and efficiency of MT30 for ISO parameters in dependence of turbine inlet temperature T_3 (**TIT**) (**combustion pressure loss is zero**) [own graph]

Combustion chamber pressure loss has an essential influence on gas turbine performance especially on GT specific work and efficiency. It may be seen in Fig. 6 for the same other parameters as in Fig. 5.

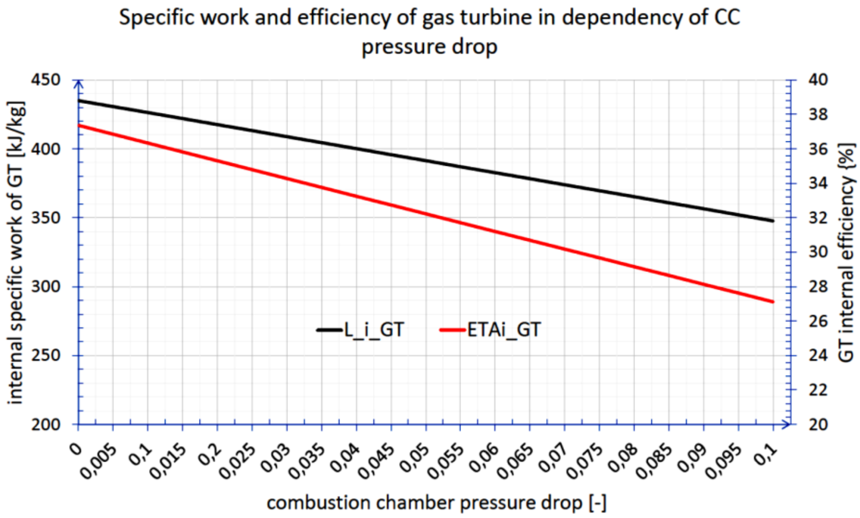

Fig. 6. Specific work and efficiency of MT30 for ISO parameters in dependence of combustion pressure loss [own graph]

It may be seen that 1% of pressure loss in combustion chamber decreases the specific work of GT about 8.5 kJ/kg (relatively it makes 2% less) and about 0.9% in thermal efficiency (2.5% relatively).

It makes an essential difference because the real pressure drop in combustion chamber is on a level of 2-5% for big power turbines up to 5-10% for small ones [5, 10].

Any disturbances in combustion process may increase the pressure drop with mentioned above effects. There are many fouling mechanisms that affect the combustor section like transition unburnt pieces, fuel nozzle coke, diffusion, flame stability problems for Dry Low NOx (DLN) and Dry Low Emission (DLE) combustors.

3. ASSESSMENT OF GAS TURBINE PERFORMANCE DECREASING DUE TO COMBUSTION CHAMBER LOSS

Gas turbine performance depends on many different parameters. The following external conditions have an essential influence on GT output and efficiency:

- ambient air temperature;
- ambient air pressure;
- elevation of GT location;
- relative air humidity;
- pressure drop in inlet filters and outlet duct;
- time of continued work between the off-line washing process due to fouling phenomena;
- pressure drop in combustion chamber.

The pressure drop in combustion chamber is an uncertainty which should be estimated, calculated or measured for the possibility of delineation the parameters of gas turbine cycle characteristic points [10-12]. The cross section through combustion chamber should be as big as possible, so there are a few kind of combustor design, annular, tubo-annular, silo and tubular. The annular type is more popular due to low pressure loss (less surface exposed to air/gas flow) and compact size. There are about twelve up to thirty annular tubes omni-directionally for one gas turbine where only two are the start-up tubes. The proper work of gas turbine depends on correct combustion process in all combustors and obtaining the even temperature distribution to turbine.

The net work ratio (NWR) for gas turbines depend on output power and compression ratio and change from idle to full load for analyzed turbine (for idling NWR is zero). NWR is about 0.4 for MT30 at nominal load. It means that 60% of turbine power goes for compressor drive and only 40% provides as output power. For that reason if the air/gas pressure in inlet to turbine decreases to 0.99 (0.01 combustion chamber pressure drop it means 1%) it will provide to 2.5% of power decreasing (1%/0.4). In a reality at 4% combustion chamber pressure drop the gas turbine output power decreases about 10%. The estimation presented in Fig.4 for MT30 marine gas turbine gives similar result.

It should be mentioned that pressure drop in combustion chamber is necessary from design point of view (pattern factor, effective cooling and mixing etc.) and flame stabilization considerations.

CONCLUSIONS

Author recognized the necessity of explanation the importance of combustion chamber pressure drop on gas turbine performance on an example of MT30 gas turbine.

The GT operator should provide required maintenance and service to keep GT in good state. Due to lack of information about the combustion chamber pressure drop it should be monitored the technical state of combustors, fuel injectors, swirlers etc. - all combustion process. Any disturbances in GT work should be detected and removed. Additional or increased pressure drop in combustion chamber may be the reason of decreasing the GT output and efficiency. An increase about 1% of pressure drop in combustion chamber is important for GT operation because decreases the accessible power of GT on a level of 2.5% with increasing the heat rate (fuel consumption) on similar level.

The combustion chambers are important parts of gas turbines and it should be known what phenomena occur there having the impact on their performance.

ABBREVIATIONS

1. **CC** - combustion chamber of gas turbine;
2. **DLE** – Dry Low Emission - a type of combustor;
3. **DLN** – Dry Low NOx - a type of combustor;
4. **GT** – gas turbine;
3. **ISO** – International Standard Organization;
4. **NWR** – net work ratio of gas turbine;
5. **SFC** – specific fuel consumption;
6. **TIT** – turbine inlet temperature T_3;
7. **Δp** - pressure drop.

WPŁYW SPADKU CIŚNIENIA W KOMORZE SPALANIA NA OSIĄGI TURBINY GAZOWEJ

W artykule omówiono problem spadku ciśnienia w procesie przepływu czynnika roboczego przez komorę spalania w turbinie gazowej. Spadek ciśnienia jest wewnętrzną wadą turbiny zależną od wielu parametrów, głównie od projektu komory i natężenia przepływu gazu przez nią. Problemem jest wyznaczenie parametrów cyklu termodynamicznego turbiny w charakterystycznych punktach, ponieważ nie jest znane całkowite ciśnienie przed i za komorami spalania. Występuje brak tej informacji ze strony producenta urządzenia, jak i również w publikacjach naukowych (brak danych eksperymentalnych, tylko rozważania i modelowania teoretyczne). Jest to ważna informacja, ponieważ spadek ciśnienia w komorze spalania ma istotny wpływ na osiągi turbiny gazowej. W artykule przedstawiono oszacowanie obniżenia osiągów turbiny z omawianego powodu. Autor artykułu uznał potrzebę zwrócenia uwagi na ten parametr i nie do końca rozeznany problem.

Słowa kluczowe: turbina gazowa, osiągi turbiny gazowej, wpływ na osiągi, pomiar spadku ciśnienia w komorze spalania

REFERENCES

[1] Cohen H., Rogers G.F.C., Saravanamuttoo H.I.H. (1996) Gas Turbine Theory. 4th Edition, Longman Group Limited, ISBN 0582236320, T.J. Press, Padstow, Cornwall

[2] Soares C. (2014) Gas Turbines. A Handbook of Air, Land and Sea Applications. Elsevier Inc., Butterworth-Heinemann, ISBN 9780124104617. https://doi.org/10.1016/C2012-0-05971-6

[3] Lefebvre A.H., Ballal D.R. (2010) Gas Turbine Combustion, Alternative Fuels and Emissions. Taylor and Francis Group, ISBN 9780429141041. https://doi.org/10.1201/9781420086058

[4] Dzida M., Kosowski K. (1989) "Experimental Investigations of Pressure Drop in the Combustion Chamber of Gas Turbine". Volume 3: Coal, Biomass and Alternative Fuels; Combustion and Fuels; Oil and Gas Application, June 1989. https://doi.org/10.1115/89-gt-247

[5] Németh R. (2017) "Combustion Process in the Gas Turbine Combustors". Corpus ID: 173176885

[6] Blevins R.D. (1984) Applied Fluid Dynamics Handbook, Van Nostrand Reinhold Co., New York

[7] Janicka J., Kuehne J., Kuenne G., Ketelheun A. (2013) "Large Eddy Simulation of Combustion Systems at Gas Turbine Conditions". In: Janicka J., Sadiki A., Schäfer M., Heeger C. (eds) Flow and Combustion in Advanced Gas Turbine Combustors. (Fluid Mechanics and Its Applications), Volume 1581. Springer, Dordrecht 2013. pp. 183-204. https://doi.org/10.1007/978-94-007-5320-4

[8] Flamme M. (2004) "New Combustion Systems for Gas Turbines (Ngt)". Applied Thermal Engineering, 24(11-12). 1551-1559. https://doi.org/10.1016/j.applthermaleng.2003.10.024

[9] Kruse S., et all (2015) "Experimental and Numerical Study of MILD Combustion for Gas Turbine Applications". Applied Energy, Vol. 148, 456-465. https://doi.org/10.1016/j.apenergy.2015.03.054

[10] Xing F., et all (2018) "Optimization Study of the Dump Diffuser in Gas Turbine to Reduce Pressure Loss". Hindawi, International Journal of Aerospace Engineering, Volume 2018, Article ID 6070782. 14 pages. https://doi.org/10.1155/2018/6070782

[11] Kotowicz J., et all (2016) ″The methodology of the gas turbine efficiency calculation″. Archives of Thermodynamics. Vol. 37, No. 4. 19–35. https://doi.org/10.1515/aoter-2016-0025

[12] Adoua R., Page G.J. (2017) ″Effect of Combustion on Turbulence in a Gas Turbine Combustion Chamber″. Proceedings of the ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition. Volume 2B: Turbomachinery. Charlotte, North Carolina, USA. June 26–30, 2017. V02BT41A046. ASME. https://doi.org/10.1115/GT2017-64694

[13] Khosravy el_Hossaini M. (2013) ″Review of the New Combustion Technologies in Modern Gas Turbines″, Progress of Gas Turbine Performance. Ernesto Benini, IntechOpen. https://dx.doi.org/10.5772/54403

[14] Breeze P. (2016) Gas-Turbine Power Generation. Elsevier Ltd. ISBN 978-0-12-804005-8. https://doi.org/10.1016/C2014-0-04848-4

[15] Edge W., 36 MW MT30 Mechanical Drive Package - Technical Description, Rolls-Royce, March 2016

[16] ISO 3977-2: 1997 Part 2, Standard reference conditions and ratings, International Standard Organization. 1997