Quantification of an Influence of a Degree of Regeneration on the Power Parameters of a Gas Turbine

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Abstract The operating mode of a gas turbine depends not only upon the intake air parameters but also upon a degree of regeneration. The paper analyses the effect of a regeneration degree on the operation of a considered GT 750-6 gas turbine using a special software developed for this purpose. Based on case calculations, the effect of a degree of regeneration on the specific power and thermal efficiency of the actual GT 750-6 gas turbine is quantified.

1 Introduction

Cycle of a gas turbine with regeneration is formed from a simple Ericson-Bryton cycle of the gas turbine by introducing a regenerative heat exchanger, in which the compressed air from the air compressor is preheated by means of heat taken away from flue gases. In this way, a necessary input of heat from fuel added in the combustion chamber reduced, if a fixed temperature at the turbine inlet is assumed, thus increasing thermal efficiency of the gas turbine cycle. A temperature decline is needed for heat transfer in the heat exchanger so far the heat exchange surfaces are of finite dimensions. A degree of regeneration influences not only the thermal efficiency and specific work of the gas turbine cycle but also it influences the heat exchanger dimensions.

2 Efficiency of a regenerative heat exchanger

The analysis of the cooled gas turbine is based on an arrangement of illustrated in **Fig. 1**. From this figure the numeric assignment of different points to which individual thermodynamic values refer is visible. Supposing that the gas mass flow is constant, the efficiency of regenerative heat exchanger is defined as a ratio of heat transferred to the air being heated to that which would be transferred by the ideal endlessly big exchanger without losses

$$\eta_R = \frac{h_{03} - h_{02}}{h_{05} - h_{02}} \tag{1}$$

where h_0 is the total enthalpy (in points 2, 3, 5 – **Fig. 1**). Ambient heat loss due to radiation being ignored, from the heat balance of a regenerative heat exchangers it follows

$$\frac{\dot{Q}_{5r}}{\dot{m}_K} = \frac{\dot{m}_T}{\dot{m}_K}\bar{c}_{p,sp,R}(t_{05} - t_{06}) = \frac{\dot{m}_2}{\dot{m}_K}\bar{c}_{p,vz,R}(t_{03} - t_{02}) = \frac{\dot{Q}_{2r}}{\dot{m}_K} \tag{2}$$

where $\dot{m}_T$ is a mass flow of flue gases at the regenerative heat exchanger inlet; $\dot{m}_K$ is a mass flow of flue air at the compressor inlet; $\dot{m}_2$ is a mass flow of flue air at the regenerative heat exchanger inlet; $\bar{c}_{p,sp,R}$ is a mean value of the isobaric specific heat capacity of flue gases (for a temperature range of t_{06} - t_{05}); $\bar{c}_{p,vz,R}$ is a mean value of the isobaric specific heat capacity of air (for a temperature range of t_{02} - t_{03}).

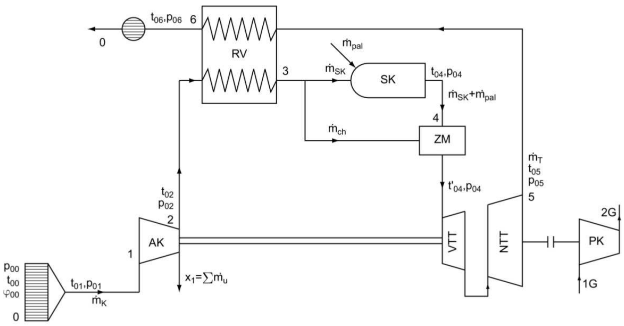

Fig. 1 A Scheme of gas turbine with regeneration.

3 Specific power output and specific cycle heat

The effective power of a gas turbine (P_{uz}) is defined as a sum of gas turbine power (VTT, NTT – **Fig. 1**) and air compressor input - negative (AK – **Fig. 1**). The specific power of a gas turbine is derived from a detail calculation of heat cycle, indirectly giving the compressor inlet-air mass flow necessary for the effective power required

$$P' = \frac{P_{uz}}{\dot{m}_K \bar{c}_{p,K} T_{01}} = \left(\frac{\dot{m}_T \bar{c}_{p,T}}{\dot{m}_K \bar{c}_{p,K}}\right) AB\eta_{m,T} - C\frac{1}{\eta_{m,K}} \tag{3}$$

where $A = \frac{T_{04}-T_{05}}{T_{04}}, B = \frac{T_{04}}{T_{01}}, C = \frac{T_{02}-T_{01}}{T_{01}}$; $\eta_{m,T}$ is the mechanical efficiency of gas turbine; $\eta_{m,K}$ is the mechanical efficiency of air compressor; $\dot{m}_T$ is a mass flow of flue gases at the gas turbine inlet; T_0 is the total temperature (in points 4, 5, 1, 2 – **Fig. 1**); $\bar{c}_{p,T}$ is the mean value of isobaric specific heat capacity of flue gases and $\bar{c}_{p,K}$ is the mean value of isobaric specific heat capacity of air in compressor. Instead of temperatures, an expansion ratio of turbine as a function of compressor pressure ratio and of pressure loss in different components of a gas turbine can be incorporated in this equation and thus in equation (5) as well. In comparison with the ideal cycle of a gas turbine, analysis of the actual one is complicated because the working substance has nor constant composition neither constant thermodynamic properties during the whole cycle. There are pressure losses both in heat exchanger and connector pipes, which together with a different mass flow (an impact of taking air for cooling, flooding of air compressor seals and an intake of cooling air into flue gas flow) operating in different components of gas turbine often have a substantial impact on the characteristic parameters of cycle. The specific heat put in the cycle shows a ratio of heat brought into a combustion chamber (SK – **Fig. 1**) to that brought by compressor inlet air

$$\dot{Q}' = \frac{\dot{m}_{SK} \bar{c}_{p,SK}}{\dot{m}_K \bar{c}_{p,K}} \{B[1-\eta_R\,(1-A)] - (1+C)(1-\eta_R)\} \tag{4}$$

where the A, B, C parameters are the same as in equation (3); η_R is the efficiency of a regenerative exchanger (RV – **Fig. 1**); $\dot{m}_{SK}$ is a air mass flow at the combustion chamber inlet; $\bar{c}_{p,SK}$ is the mean value of isobaric specific heat capacity of flue gases in the combustion chamber.

4 Thermal efficiency of a gas turbine

An important indicator of the economy of the energy transfer into mechanical work is the thermal efficiency defined as a specific power - to - specific heat ratio. After substitution and modification we obtain

$$\eta_t = \frac{\dfrac{P_{uz}}{\dot{m}_K \bar{c}_{p,K} T_{01}} = \left(\dfrac{\dot{m}_T \bar{c}_{p,T}}{\dot{m}_K \bar{c}_{p,K}}\right) AB\eta_{m,T} - C\dfrac{1}{\eta_{m,K}}}{\dfrac{\dot{m}_{SK} \bar{c}_{p,SK}}{\dot{m}_K \bar{c}_{p,K}}\{B[1-\eta_R(1-A)] - (1+C)(1-\eta_R)\}} \tag{5}$$

where the A, B, C parameters are the same as in equation (3). The A parameter is a function of pressure losses and pressure ratio of the air compressor, the B parameter defines a ratio of the total temperature of flue gases at the turbine inlet and the total temperature of air at inlet into an air compressor and the C parameter is a function of the pressure ratio of the compressor.

5 Results

Derived equations have been verified by analysing the real cycles of gas turbines in operation based on the results from technical measuring. In investigating an effect of a regeneration degree, defined by the efficiency of a regenerative heat exchanger, on the thermal efficiency and the specific power output an arrangement of a GT 750-6 gas turbine is considered. **Fig. 2** shows that regeneration has a greater effect on improving the thermal efficiency at lower pressure ratio. Pressure ratio at which the thermal efficiency amounts to its maximum shifts with an increasing degree of regeneration (η_R) towards lower values. The influence of a regeneration degree on the specific power output (**Fig. 3**) is negligible on condition that due to a change in regeneration degree, there are no changes in pressure losses in the regeneration heat exchanger as well in other parts of a the turbine. The maximum value of the specific power output corresponds to various values of the thermal efficiency (**Fig. 4**) depending on a degree of regeneration. In case without regenerative heat exchanger ($\eta_R = 0$) the maximum specific power output is achieved at lower compression, as compared to that at which the maximum thermal efficiency is obtained (**Figs. 2** and **3**). Increasing the pressure ratio above the value at which the maximum thermal efficiency is achieved brings about an increase in a temperature of compressed air (and the needed of heat input into the combustion chamber reduces), thereby increasing the thermal efficiency until the compression limit. If compression continues to increase, the thermal efficiency shows a fall (**Fig. 4**), since there is a decrease in the adiabatic efficiency of air compressor and gas turbine as wheel, and the potential of thermal energy contained in flue gases at the gas turbine inlet is reduced.

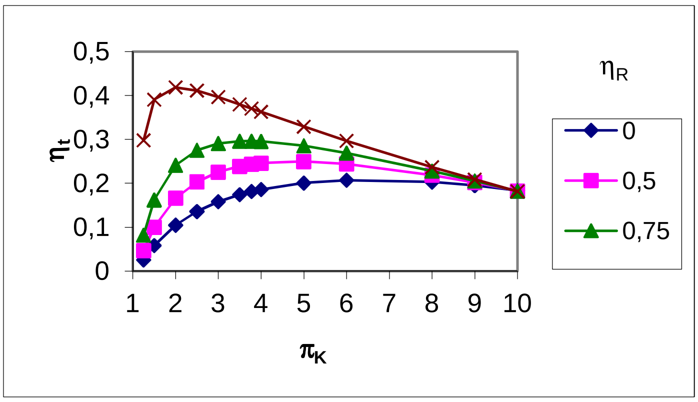

Fig. 2 Thermal efficiency dependence on pressure ratio ($T_{04}/T_{01} = 3,5$).

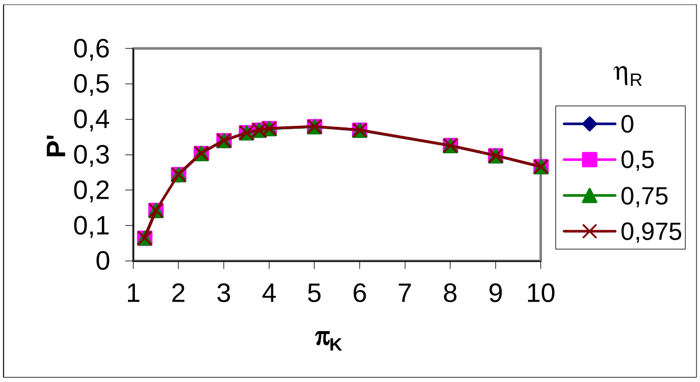

Fig. 3 Specific power output dependence on pressure ratio (T_{04}/T_{01} = 3,5).

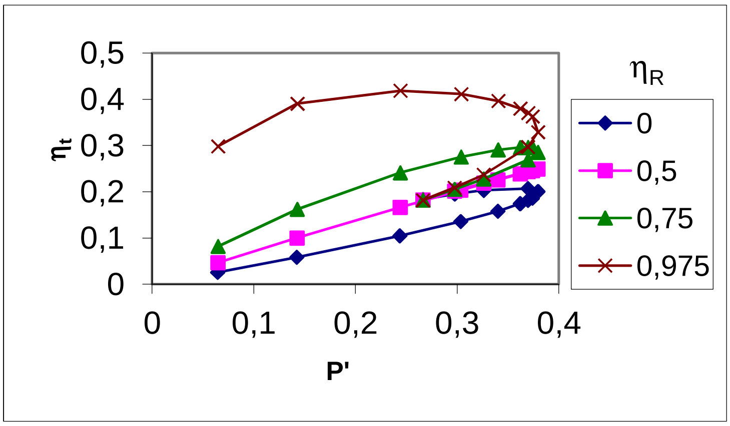

Fig. 4 Dependence of thermal efficiency and specific power output (T_{04}/T_{01} = 3,5).

If values of a degree of regeneration rise, the maximum thermal efficiency is achieved at lower pressure ratio and a subsequent increase in pressure ratio results in decreasing the thermal efficiency although the specific power output increases. It is caused by less usage of the potential of thermal energy contained in flue gases at the regeneration heat exchanger inlet.

6 Conclusions

The paper presents the derived computing relationship, which are derived in such a way that they are as universal as possible and suitable for software processing. Based on the developed software, in a case study an effect of a regeneration degree on the power parameters of the cycle of a gas turbine GT 750-6 is analysed. The computing results suggest that in designing a gas turbine it implement the optimization not only in terms of the maximum thermal efficiency but also the maximum specific power output.

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References

[1] Ridzoň, F.: Spaľovacia turbína s regeneráciou tepla. Habilitačná práca. Strojnícka fakulta STU, Bratislava 2008.

[2] Kousal, M.: Spalovací turbíny, SNTL, Praha 1980.

[3] The Design of Gas Turbine Engines Thermodynamics and Aerodynamics. International Gas Turbine Institute, Atlanta 1998.