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The Effect of Turbine Blade Cooling on the Performance of Recuperative Cycles for Gas Turbines Applications

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Nowadays the constantly increasing demand for energy production has a strong impact on the environmental pollution. Therefore, the development of more efficient gas turbines is a key factor for decreasing pollutant emissions. The increased combustion temperature can significantly improve gas turbine cycle efficiency. However, this temperature is limited by the maximum allowable temperature of the turbines blades material. Another way to improve cycle performance is the use of gas turbine recuperation by the installation of heat exchangers for preheating the cold air before it enters the combustor which can lead to improved efficiency, important fuel reduction and thus, to low emissions. In this work the impact of the turbine air cooling requirements on different recuperative cycles efficiencies is investigated. A thermodynamic cycle analysis tool capable to calculate the performance of gas turbines cycles with and without the inclusion of the effects of cooling air flow rates is developed. In the analysis three recuperative cycles are investigated. The first configuration under investigation is the conventional recuperative cycle in which a heat exchanger is employed downstream the last turbine, in the second configuration, the alternative recuperative cycle, the heat exchanger is placed between the low pressure and the intermediate pressure turbine while in the last configuration, the staged heat recovery recuperative cycle, two heat exchangers are installed, the first between the low pressure and the intermediate pressure turbine and the second downstream the last turbine. For the completeness of the work, the first part shows the cycles efficiency without including the coolant mass flow for the turbine. The second part focuses on the performance assessment of the recuperative cycles, by taking into consideration the demands for turbine blade cooling. A tool for the calculation of the required coolant flow rates for each turbine, based on the theory of Young and Wilcock, is presented. A detailed parametric study is conducted for a wide range of operational conditions by taking into account three different values of maximum allowable blade metal temperatures and the results of the thermodynamic cycles efficiencies with and without turbine blade cooling are compared and discussed. In the last part of the work a detailed model of a helicopter engine is presented and the impact of the coolant mass flow rates on the engine performance is examined.

1. Introduction

The turbine inlet temperature (TIT) is one of the most important parameters of gas turbines since the increase of TIT can significantly raise efficiency. During the last decades, there has been a lot of effort to improve materials properties and many temperature resistant materials such as nickel-chromium alloys and ceramics are now used in gas turbine applications. However, even with these temperature resistant materials, for high TIT such as 1,850 K the need for cooling of the turbine blades is inevitable. Air from the compressor stages is extracted in order to cool the turbines blades. The coolant air flows inside the turbine blade, it leaves the blade through holes that exist in various positions in the surface of each blade and is mixed with the gas that is expanded through the turbines. However, the extraction of air for cooling the turbines has a strong impact on gas turbine efficiency. For this reason, taking into account the effect of turbine cooling is vital for the proper evaluation of a gas turbine thermodynamic cycle, especially during the preliminary design of new cycles. In this work, the effect of turbine blade cooling on different Brayton recuperative cycles for gas turbine applications is

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studied. Three recuperative cycles, with heat exchangers (HEXs) placed at different positions, are studied for a wide range of operational conditions and for three different blade maximum allowable temperatures. In the first configuration, named as conventional recuperation (CR), the HEX is place downstream the last turbine while it the second, named as alternative recuperation (AR), the HEX is placed between the turbines. In the third cycle, named as staged heat recovery cycle (SHR), two HEXs are installed the first one (primary HEX) between the turbines and second one (secondary) after the last turbine. The HEXs are used in order to preheat the compressor discharge before it enters the combustion chamber, and efficiency is improved and fuel consumption is reduced. HEXs are widely used for improving efficiency also in other applications (Pintarič et al., 2015) and the retrofit tools by Yong et al. (2015). The AR and SHR cycles have been introduced by Dellenback (2006). In previous work (Salpingidou et al., 2016) these cycles have been investigated for a wide range of overall pressure ratio (OPR), without taking into account the effect of the turbine blade cooling. In the current work the three recuperative cycles are calculated again and the effect of the turbine blade cooling is incorporated. For each cycle and for every different OPR value the coolant flow demands for every turbine are calculated for three blade maximum allowable temperatures. Proper thermodynamic models that can calculate both cooled and uncooled turbines have been developed for each recuperative cycle. The calculation of the coolant flowrates and the cooled turbine are based on the work of Young and Wilcock (2002b) and the second part Young and Wilcock (2002a). In the last part of this work a helicopter recuperative engine and the impact of turbine blade cooling on the efficiency is investigated. The performance of the engine is studied with and without taking into account the coolant demands. The engine data were taken from the work of Shapiro and Levy (Shapiro and Levy, 1990). The thermodynamic models of the recuperative cycles and the helicopter engine were created in CAPE-OPEN/COFE flowsheet environment with COCO simulator software, (COCO - the CAPE-OPEN simulator). Custom components based on Young and Wilcock (2002a) theory were created for the calculation of the cooled turbines.

2. Theory

2.1 Thermodynamic model

The first step of the analysis is the creation of the thermodynamic model in CAPE-OPEN. Figures 1 and 2 show the thermodynamic models of an uncooled and cooled CR cycle. The first turbine is the high pressure turbine (HPT) and drives the compressor, while the last turbine is the power turbine (PT) and produces the net work output of the cycle. Regarding the cooled cycle, air is extracted from the compressor in order to cool the turbines, the rest part of the compressor discharge air enters the HEX and is preheated.

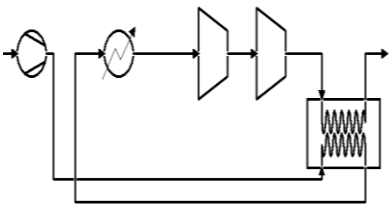

Figure 1: CR cycle without cooling.

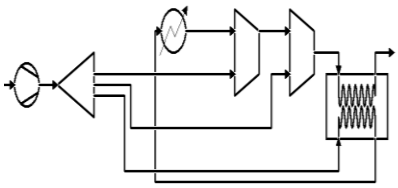

Figure 2: CR cycle with cooling.

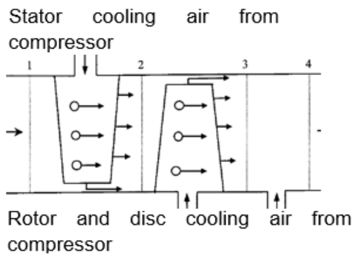

Figure 3: Schematic diagram of a cooled turbine stage (Wilcock et al., 2005).

Table 1: Cycle parameters.

Parameter	Value
Polytropic Compressor Efficiency	0.9
Polytropic Turbine Efficiency	0.87
Pressure Losses Combustion Chamber	3 %
Pressure Losses Heat Exchanger	2 %
Turbine Inlet Temperature (TIT)	1,500 °C
HEX Effectiveness Range	0.5-0.9
Air Inlet Conditions	15 °C, 101,325 Pa

The main parameters of the cycle such as polytropic efficiency, TIT, etc, where kept the same as in Dellenback's work (Dellenback, 2006) and they are summarized in Table 1. More information about each cycle and the equations of the thermodynamic model can be found in the work of Dellenback (2006) and Salpingidou et al. (2016).

2.2 Model for the calculation of the coolant mass flow rates

For the calculation of the coolant mass flow rates the theory of Holland and Thake (1980) and Young and Wilcock (2002a) was used. In this model, the stator and the rotor are treated separately. The main equations and parameters that are shown below:

- The internal flow cooling efficiency $\eta_{c,int}$ reflects the heat transfer effectiveness inside the blades, Eq(1), where $T_{oc,x}$ is total coolant temperature at the exit of the blade (before the mixing), $T_{oc,i}$ is the total coolant temperature at the inlet of the blade and $T_{m,int}$ is the internal metal temperature.

$$\eta_{c,int}=\frac{T_{oc,x}-T_{oc,i}}{T_{m,int}-T_{oc,i}} \tag{1}$$

- The film cooling effectiveness ε_f describes the level of a specific cooling technology, Eq(2), where T_{og} is the total temperature of the mainstream gas and T_{aw} is the mean adiabatic wall temperature. In the film cooling technology a film of the coolant air is created across the blade.

$$\varepsilon_f=\frac{T_{og}-T_{aw}}{T_{og}-T_{oc,x}} \tag{2}$$

- A metal Biot number, Bi_{met}, and a TBC Biot number, Bi_{tbc}, are introduced for the blade metal and the thermal coating respectively, Eq(3) and Eq(4), where $T_{m,ext}$ is the maximum allowable metal temperature and T_w is the temperature at the outer surface of the blade.

$$Bi_{met}=\frac{T_{m,ext}-T_{m,int}}{T_{aw}-T_w} \tag{3}$$

$$Bi_{tbc}=\frac{T_w-T_{m,ext}}{T_{aw}-T_w} \tag{4}$$

- The blade cooling effectiveness, ε_o Eq(5), which is linked to the desired (allowable) temperature of the metal at the external side of the blade.

$$\varepsilon_o=\frac{T_{og}-T_{m,ext}}{T_{og}-T_{oc,i}} \tag{5}$$

- The cooling flow rates $\frac{m_c}{m_g}$ are calculated using Eq(6), where a cooling flow rate factor K_{cool} (based on A_{surf}, A_g, Cp_c, Cp_g) and a Stanton number St_g are introduced.

$$\frac{m_c}{m_g}=\left(\frac{A_{surf}}{A_g}\right)*\left(\frac{Cp_g}{Cp_c}\right)*St_g*m_{c+}=K_{cool}*m_{c+}=K_{cool}*\frac{T_{aw}-T_w}{T_{oc,x}-T_{oc,i}} \tag{6}$$

Wilcock et al. (2005) suggested in their work some values for some parameters such as, K_{cool}, Bi_{met}, Bi_{tbc} and $\eta_{c,int}$ based on the cooling technology level.

For the calculation of the cooled turbines the first law of thermodynamics is applied in stator, Eq(7), and rotor, Eq(8). Equations follow the numbering of Figure 3, Wilcock et al. (2005), and h represents enthalpy.

$$m_g*(h_{og,1}-h_{og,2})+m_c*(h_{oc,1}-h_{og,2})=0 \tag{7}$$

$$m_g*(h_{og,2}-h_{og,3})+m_c*(h_{oc,i}-h_{og,3})=Work \tag{8}$$

3. Results

The results for the three recuperative cycles for a wide range of OPR (OPR = 5 - 40), three HEX effectiveness values (ε = 0.5-0.9) and three different allowable metal Temperature ($T_{m,ext}$ = 1,078 K, 1,333 K, 1,423 K) for nickel-base superalloys for blading applications in aircraft engines (Muktinutalapati, 2011) are shown in Figures 4, 5, 6 and 7. The comparative value is the cycle efficiency which expresses the percentage of the added heat that is converted to useful work/work output produced by the power turbine and is given in Eq(9).

$$\eta = \frac{\text{Useful Work}}{\text{Added Heat}} \tag{9}$$

The results show the importance of including the cooling flow in the thermodynamic cycle model. The "cooled" cycles have reduced efficiency since an important part of the compressor discharge air is not expanded through the turbines. This reduction is more intense in cases of low allowable metal temperature ($T_{m,\,ext}$ = 1,078 K), since the thermal resistance of the material is low and thus the demands for cooling are higher. Another important conclusion is that the reduction of efficiency is higher in CR cycle that in the alternative cycle. For example, in Figure 4, for OPR = 20 and $T_{m,\,ext}$ = 1,078 K the reduction for the CR is 13 % while for the AR cycle is 7 %. This can be easily explained since in case of AR cycle a HEX is incorporated between the turbines, therefore the air enters the PT with reduced enthalpy and thus, reduced temperature. This fact has a strong impact on the critical OPR value at which the AR cycle starts to outperform the CR cycle. More specifically, for $T_{m,\,ext}$ = 1,333 K, 1,423 K that value does not change importantly, however for $T_{m,\,ext}$ = 1,078 K that value is much lower. In Figure 6 the critical OPR for uncooled cycles is 17 while for cooled cycles and $T_{m,\,ext}$ = 1,078 K is 13. As HEX efficiency gets lower the OPR difference between cooled and uncooled cycles gets higher. Regarding the SHR cycle, Figure 7 shows that the efficiency reduction is higher in case of low HEX effectiveness, which is a consequence of the lower temperature of the air at the PT inlet.

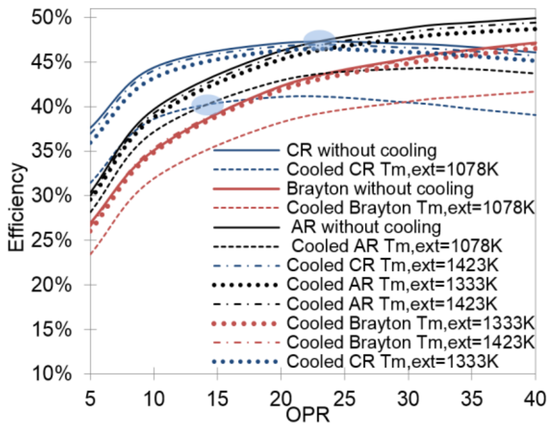

Figure 4: Cycles efficiency for HEX ε = 0.5.

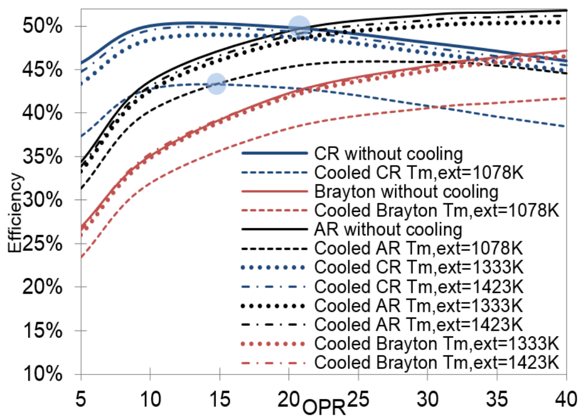

Figure 5: Cycles efficiency for HEX ε = 0.7.

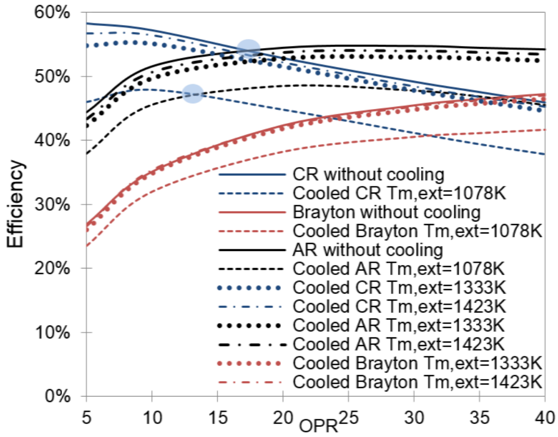

Figure 6: Cycles efficiency for HEX ε = 0.9.

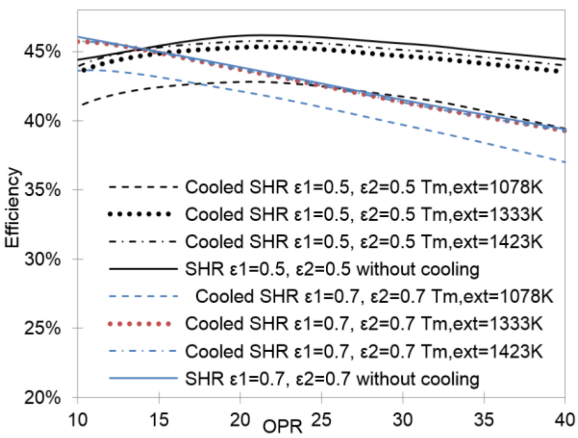

Figure 7. SHR efficiency.

4. Application on helicopter engine

The last part of this work investigates the impact of turbine blade cooling on the performance of a recuperative turboshaft engine for helicopters. For this study data from the work of Shapiro and Levy (1990), Table 2, were used and a thermodynamic model for this engine was created. The engine consists of a compressor, one turbine that drives the compressor and one power turbine connected to a shaft. A heat exchanger is placed between the turbines, AR cycle. A schematic illustration of the cycle is shown in Figure 8. In order to validate the model the performance of the engine at the design point was calculated and the results were in very close agreement with a relative error less than 0.5 %.

Table 2 Helicopter engine parameters.

Parameter	Value
Compressor Efficiency	0.78
Power Turbine Efficiency	0.9
Compressor Pressure Ratio	11.2:1
Overall Pressure Loss Ratio	18 %
Turbine Inlet Temperature (TIT)	1,400 K – 1,700 K
HEX Effectiveness Range	0.5 - 0.7
Engine airflow	5 kg/s

The engine model was simulated for four TITs (1,400 K, 1,500 K, 1,600 K, 1,700 K) and two HEX effectiveness (0.5, 0.7) with and without including the demanded air for cooling. The calculation of the coolant mass flow rates and cooled turbines was based on the model of Young and Wilcock (2002a) which was previously described. The allowable blade metal temperature was considered 1,078 K, the same as in the work of Young and Wilcock (2002a). For the proper evaluation of the results the SFC (specific fuel consumption) and thermal efficiency of the cycle were calculated. The results are in Fig 9 and Fig 10.

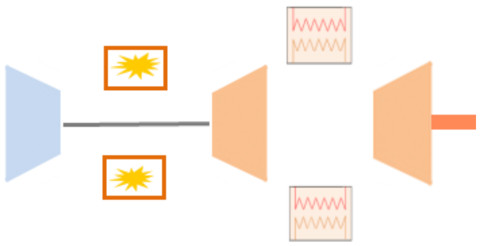

Figure 8: Schematic illustration of a recuperative turboshaft engine.

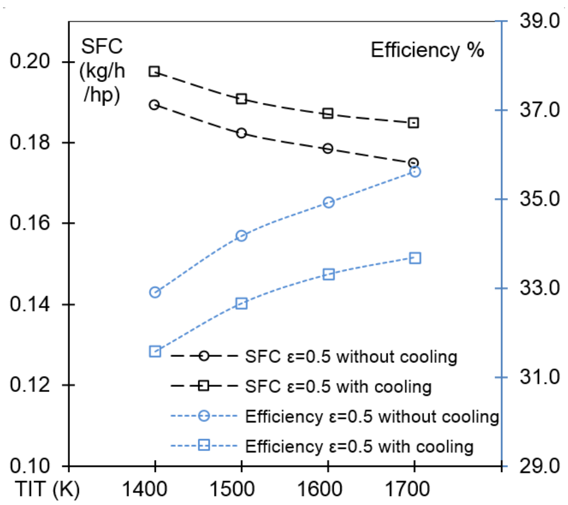

Figure 9: Results of a recuperative (HEX ε = 0.5) turboshaft, with and without cooling.

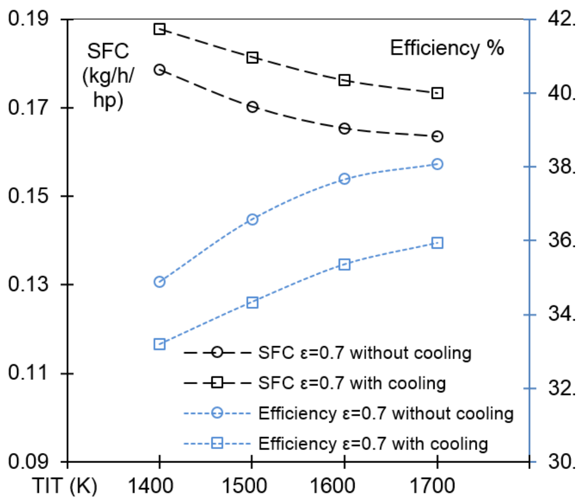

Figure 10: Results of a recuperative (HEX ε = 0.7) turboshaft, with and without cooling.

The results show that the performance of the engines drops when the turbines are cooled. This is a normal consequence of the unexploited air which is used for cooling and is not expanded through the turbines. Specifically, the cooled cycles have increased SFC round 1 % which an important value especially for flight applications. The thermal efficiency is significantly decreased and especially for higher TIT such as 1600 K and

1,700 K the thermal efficiency is almost 2 % lower. The main outcome of the results is the importance of including the coolant air in the complete model of the engine.

5. Conclusions

At the present work, the effect of turbine blade cooling on the performance of different recuperative cycles for gas turbine applications is investigated. Three recuperative cycles are investigated and a turboshaft engine for flight application.

Regarding the three cycles the main conclusion are the following:

- Part of the compressor discharge air is used for cooling the turbines and therefore the efficiency of the cooled cycles is significantly lower.
- As the allowable metal temperature decreases the efficiency of the cooled cycle gets also lower.
- The reduction of efficiency is more intense in CR cycle than in the AR cycle, since the CR cycle is more sensitive to the value of allowable metal temperature.
- The critical OPR at which the AR cycle outperforms the CR cycle, shifts to lower values for low allowable metal temperature ($T_{m,\,ext}$ = 1,078 K).

Regarding the helicopter engine the main conclusions are the following:

- The cooled cycle presents reduced thermal efficiency and increased SFC.
- For high TIT values the efficiency reduction is more intense.

The above conclusions highlight the importance of taking into account the turbine blade cooling for the proper evaluation of a cycle, especially for conditions corresponding to high turbine inlet temperatures.

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