Estimation of cooling flow rate for conceptual design stage of a gas turbine engine

EP Filinov1, VS Kuz’michev1, A Yu Tkachenko1, YaA Ostapyuk1 and IN Krupenich2

Abstract
Development of a gas turbine engine starts with optimization of the working process parameters. Turbine inlet temperature is among the most influential parameters that largely determine performance of an engine. As typical turbine inlet temperatures substantially exceed the point where metal turbine blades maintain reasonable thermal strength, proper modeling of the turbine cooling system becomes crucial for optimization of the engine’s parameters. Currently available numerical models are based on empirical data and thus must be updated regularly. This paper reviews the published information on turbine cooling requirements, and provides an approximation curve that generalizes data on all types of blade/vane cooling and is suitable for computer-based optimization.

Keywords
Cooling systems, gas turbines, gas turbine aero-thermodynamics, airbreathing engines, engine modelling/simulation, gas turbine performance, turbine blade cooling, turbine design, turbine modelling, turbines

Date received: 29 July 2020; accepted: 15 April 2021

Introduction
The primary trend in improving efficiency of gas turbine engines is the systematic increase of the working process parameters: turbine inlet temperature (TIT) and overall pressure ratio (OPR) and bypass ratio (BPR) together with increasing the efficiency of engine’s elements. Engine’s reliability throughout its lifetime plays a crucial role as well.

Maximum TIT has reached 1600–2000 K while a metal turbine blade maintains reasonable thermal strength at much lower temperatures around 1200 K, so the TIT increases at a substantially higher pace (see literature1,2 for more details). That means that engine’s lifetime and reliability could be guaranteed only by cooling turbine blades and vanes, or by switching to new materials like ceramics.

Cooling of turbine have high influence on efficiency of engine, comparable to turbine aerodynamic performance3–9 and should be taken into the account when optimizing the working process of gas turbine engine.

One of the first models to predict cooling requirements was developed by Holland and Thake in 1980.10 Authors that contributed to developing such models include Ainley,11 Consonni,12 Torbidoni and Horlock,13,14 Vadlamudi, Kommineni and Katuru,15,16 Jordal,17 Jiang and Chen.18 These models are constantly evolving and becoming more comprehensive.

Results based on such models show linear relationship between TIT and cooling air flow rate, calculating lower cooling requirements and overestimating engine efficiency, so more complex models are being developed, including work by Yin, Tiemstra and Rao,1,19,20 Kopelev,2 Shvets and Dyban,21 Li and Liu,22 Li, Gu and Song.23,24

More complex and physics-based models, unfortunately, require more detailed information on turbine geometry, which is usually not available at the initial stages of engine designing. It must be noted that there are limited publications on design and development of turbine cooling at the initial design stages that
Filinov et al. 2015 shows need for more research in this area. This study was focused on addressing this issue.

Traditional algorithms to estimate required cooling air flow rate use the cooling intensity $h$ (see the equation (2)). Cooling requirements calculated using publicly available models connecting cooling intensity with relative cooling flow rate$^{21,25–31}$ show dispersion up to 3.5 percent for a given cooling type, which is too high for reliable calculations. At the same time, increased cooling flow rate impacts both turbine efficiency and its exhaust temperature resulting in increased specific fuel consumption (SFC)$^{32}$.

Accuracy of cooling flow rate estimation at the conceptual design phase determines effectiveness of the optimization of working process parameters. For this reason, it is important to analyze the available models connecting cooling intensity with relative cooling flow rate.

**Literature search and analysis of the cooling efficiency of the aircraft gas turbines**

The following types of turbine blade cooling are currently available:

- convective cooling,
- convective film cooling,
- porous cooling.

Cooling flow rate includes the following constituents:

$$G_{cl} = G_{cl,vane} + G_{cl,\ blade} + G_{cl,\ disk} + G_{cl,\ leak}$$

where $G_{cl,vane}$ – flow rate for cooling turbine vanes, kg/s;

$G_{cl,\ blade}$ – flow rate for cooling blades, kg/s;

$G_{cl,\ disk}$ – flow rate for cooling turbine disk, kg/s;

$G_{cl,\ leak}$ – cooling air flow leaks, kg/s.

Required cooling flow rate is a function of cooling type and cooling intensity $\theta$:

$$\theta = \frac{T_4 - T_{\ blade}}{T_4 - T_{\ cooling}},$$

where $T_4$ – stagnation temperature of the combustion chamber exhaust, K;

$T_{\ blade}$ – blade temperature, K;

$T_{\ cooling}$ – stagnation temperature of the cooling air, K.

Cooling flow diagram is on Figure 1.

Published data on various turbine cooling types was analyzed and the results are shown on Figures 2 to 4 as cooling intensity ($\theta$) vs relative flow rate ($\bar{G}_{cl}$) charts:

$$\bar{G}_{cl} = \frac{G_{cl}}{G_{2i}}$$

where $G_{2i}$ – main annulus flow rate at the vane assembly inlet or turbine blade assembly inlet. Lines 8 and 9 of the Figure 2, and line 5 of the Figure 3 show the efficiency of vane cooling. The remaining lines either show the efficiency of blade cooling or the authors made no distinction between these two.

Cooling intensity curves are apparently specific to a certain design of cooling system and turbine itself, but these specific features are impossible to take into the account at the conceptual design stage because of very high level of uncertainty. Therefore, an averaged curve for each cooling type (Figures 2 to 4) was established. These envelope curves are shown on Figure 5.

Next, a universal approximation curve was determined for all types of cooling. This approximation curve is described in the next section. Second and third order polynomial curves were used to describe
the cooling intensity because they provide both sufficient accuracy and robustness without unacceptable fluctuations.

Separate cooling flow rates for the convective and film cooling should be established for the convective film cooling, as the cooling air leaves the blades (or vanes) at different sections of the turbine. Tables 1 to 3 show the fraction of film cooling as a function of TIT or cooling intensity. Based on the data shown in Tables 1 to 3 the share of film cooling of 0.7 may be used for the conceptual design phase.

Figure 6 shows the relative cooling flow rate for the turbine disc cooling vs TIT.29

Figure 7 shows the relative cooling air flow leaks vs maximum turbine inlet temperature.

As it was mentioned before, higher cooling flow rates increase the specific fuel consumption because of the reduced efficiency of turbines. For this reason, it is important to accurately estimate turbine efficiency reduction as a function of cooling air flow rate. Open sources of information on turbine blades and vanes cooling were analyzed and the data was generalized as shown on Figure 8.

**Calculation of required cooling flow rate for an aviation gas turbine**

Overall cooling flow rate is a sum of flow rates for cooling each turbine spool:

\[
G_{cl} = \sum_{i=1}^{n} G_{cl,i}
\]

where \(i = 1, n\) – number of turbine spools (high pressure, medium pressure, low pressure, free turbine),

\(G_{cl,i}\) – cooling air flow rate calculated using the equation (1).
Figure 4. Intensity of porous cooling.

Figure 5. Generalization of various cooling types.

Table 1. Fraction of the film cooling flow rate.  

| Cooling type        | $G_d$ (%) | $T_{\text{inlet}}$ (K) | 1680 | 1720 | 1850 | 1950 | 2000 |
|---------------------|-----------|-------------------------|------|------|------|------|------|
| Film                |           |                         | 0.00 | 1.60 | 1.60 | 4.00 | 4.00 |
| Convective film     | 2.50      |                         | 3.50 | 4.50 | 6.00 | 5.80 |
| Share of film cooling| 0.00      |                         | 0.35 | 0.60 | 0.67 | 0.69 |

Table 2. Fraction of the film cooling flow rate.  

| Cooling type         | $G_d$ (%) | $T_{\text{inlet}}$ (K) | 1300 | 1400 | 1600 | 1800 |
|----------------------|-----------|-------------------------|------|------|------|------|
| Convective           | 0.5       |                         | 1.0  | 2.0  | 2.0  | 3.0  |
| Film                 | 0.0       |                         | 2.0  | 45   | 8.0  |
| Convective film      | 0.5       |                         | 3.0  | 6.5  | 11.0 |
| Share of film cooling| 0.00      |                         | 0.67 | 0.69 | 0.72 |
Table 3. Fraction of the film cooling flow rate.34

| Cooling type             | \( G_{cl} \) (%) |
|-------------------------|-------------------|
| Cooline intensity, \( \Theta \) |
| 0.1                     | 0.2               | 0.3               |
| Convective              | 1.00              | 2.00              | 3.00              |
| Film                    | 2.00              | 4.00              | 7.00              |
| Convective film         | 3.00              | 6.00              | 10.00             |
| Share of film cooling   | 0.67              | 0.67              | 0.70              |

For a given turbine inlet temperature \((T_4^* = \text{const})\)

1) Cooling intensity of the turbine vanes is calculated using the equation (2).
2) Cooling type for vanes is determined based on TIT:
   \( T_4 = 1300 \ldots 1600 \) K – convective cooling;
   \( T_4 = 1600 \ldots 1850 \) K – convective film cooling;
   \( T_4 = 1850 \ldots 2100 \) K – porous cooling.

Figure 6. Influence of maximum turbine inlet temperature on the relative cooling flow rate for the turbine disc cooling.

Figure 7. Influence of the maximum turbine inlet temperature on the relative cooling air flow leaks.29,33

Figure 8. Reduction of turbine efficiency ratio as a function of total relative air flow rate for cooling of blades, vanes, and turbine disk.33,35
3) Relative cooling air flow rate is determined using Figure 5. The following equations derived from this graph may also be used:

\[ \bar{G}_{cl,\text{conv}} = 48.52 \cdot \theta^3 - 21 \cdot \theta^2 + 5.377 \cdot \theta - 0.023, \]
\[ \bar{G}_{cl,\text{film}} = 56.568 \cdot \theta^2 - 47.418 \cdot \theta + 11.952, \] (3)
\[ \bar{G}_{cl,\text{porous}} = 212.55 \cdot \theta^2 - 290.63 \cdot \theta + 102.41 \]

4) Cooling air flow rate for vanes cooling:

\[ G_{cl,vane} = \bar{G}_{cl} \cdot G_{air} \cdot 4 / 100, \text{ kg/s} \]

5) Cooling intensity of turbine blades is calculated:

\[ \theta = \frac{T_4^- \text{blade} - T_\text{blade}}{T_4^- \text{cooling}}. \]

6) Required relative air flow rate for blades cooling is determined using equations (3). Analysis shows that relative air flow rate for vanes and blades may be determined using the same graphs or equations.

7) Cooling air flow rate for blades cooling:

\[ G_{cl,\text{blade}} = \bar{G}_{cl} \cdot G_{air} \cdot 4_{\text{blade}} / 100, \text{ kg/s} \]

where \( G_{air} \cdot 4_{\text{blade}} = G_{air} \cdot 4 + G_{cl,vane}. \)

8) Required cooling air flow rate for disk cooling may be determined using the following equations (see Figure 6):

\[ \bar{G}_{cl,\text{disk}} = 3 \cdot 10^{-6} \cdot T_4^- 2 - 0.0063 \cdot T_4^- + 3.4643, \]
\[ G_{cl,\text{disk}} = \bar{G}_{cl,\text{disk}} \cdot G_{air} \cdot 4_{\text{blade}} \]

9) Total cooling flow rate for the turbine \( G_{oiji} \) is calculated using the equation (1).

**Determining required cooling flow rate for variable turbine inlet temperature \( (T_4^- = \text{var}) \)**

The algorithm for determining required cooling flow rate is similar to previously described. Instead of equations (3), the universal approximation curve (generalizing various types of cooling as a function of cooling intensity) should be used (see Figure 5). Robust optimization process requires continuous smooth goal function, while using separate curves for various cooling types leads to efficiency leaps when switching from one cooling type to another. Universal approximation curve, established for a wide range of turbine inlet temperatures solves this problem:

\[ G_{cl} = 12.423 \cdot \theta^3 - 6.378 \cdot \theta^2 + 4.273 \cdot \theta - 0.0225 \]

Universal approximation curve is obviously less accurate than a set of curves for each type of cooling, but its maximum error is estimated at 1.5 percent, which is acceptable at the initial design stages.

For instance, consider a task of optimizing working process parameters of a turbofan engine. Results of this optimization are shown on Figure 9: specific fuel consumption as a function of TIT. You may see that SFC leaps around \( TIT = 1600K \) and \( TIT = 1850K \) due to the change in turbine cooling type. Automated optimization may lead to unrealistic results in this case, while universal approximation curve for turbine cooling solves this problem, making the goal function continuous and smooth.

**Conclusion**

Constant improvements to the turbines’ designs and their materials require regular updates to the regression models of cooling efficiency. No theoretical functions are available for the conceptual design stage, while existing approximations of empirical data...
shows high dispersion of over 3.5 percent. This study analyzed and generalized published empirical data on gas turbine cooling efficiency. We are planning to expand our approximation curve to include other prospective cooling types and turbine designs, including described in literature.\textsuperscript{36,37}

The models developed in this study take into the account the air for cooling of vanes, blades and disks, as well as cooling air leaks. These models laid foundation for two algorithms for estimation of cooling air flow rates: for a fixed turbine inlet temperature and for the optimization purposes (when TIT is variable). Variable TIT required generalization of the curves for various types of cooling. Use of the universal approximation curve eliminates efficiency leaps and thus false design point calculations and is suitable for computer-aided design systems.

Declaration of Conflicting Interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The research was supported by the Ministry of Science and Higher Education of the Russian Federation (Grant No. 0777-2020-0015).

ORCID iDs
EP Filinov https://orcid.org/0000-0002-8406-3687
IN Krupenich https://orcid.org/0000-0003-2300-0823

References
1. Tiemstra FS. Design of a semi-empirical tool for the evaluation of turbine cooling requirements in a preliminary design stage. Master’s thesis, 2014, p.147.
2. Kopelev SZ. Cooled gas turbine blades. Moscow: Nauka, 1983, p.146.
3. Ba W, Wang Z, Li X, et al. Three-dimensional optimal design of a cooled turbine considering the coolant requirement change. Open Physics 2019; 17: 768–778.
4. Ba W, Wang X-C, Li X-S, et al. Definition of cycle based comprehensive efficiency of a cooled turbine. Energy 2019; 168: 601–608.
5. Young JB and Horlock JH. Defining the efficiency of a cooled turbine. J Turbomach 2006; 128: 658–667.
6. Salpingidou C, Tsakmakidou D, Vlahostergios Z, et al. The effect of turbine blade cooling on the performance of recuperative cycles for gas turbines applications. Chem Eng Trans 2017; 61: 1027–1032.
7. Sahu MK and Sanjay Y. Investigation of the effect of air film blade cooling on thermoeconomics of gas turbine based power plant cycle. Energy 2016; 115: 1320–1330.
8. Song Y, Gu C-W and Ji X-X. Development and validation of a full-range performance analysis model for a three-spool gas turbine with turbine cooling. Energy 2015; 89: 545–557.

9. Vassiliev V, Granovskiy A and Lomakin N. Impact of turbine blade internal cooling on aerodynamic loss. In: Proceedings of the ASME Turbo Expo 2A V02AT38A016, Montreal, Canada, June 15–19, 2015.
10. Holland MJ and Thake TF. Rotor blade cooling in high pressure turbines. J Aircr 1980; 17: 412–418.
11. Ainley DG. Internal air cooling for turbine blades: a general design study. Aeronautical Research Council Reports and Memorandum, 1957, pp.3013.
12. Consonni S. Performance prediction of gas/steam cycles for power generation. PhD thesis, Princeton University, 1992.
13. Torbidoni L and Horlock JH. A new method to calculate the coolant requirements of a high-temperature gas turbine blade. J Turbomach 2005; 127: 191–199.
14. Horlock JH, Watson DT and Jones TV. Limitations on gas turbine performance imposed by large turbine cooling flows. In: Proceedings of ASME TURBOEXPO 2000, Munich, Germany, May 8–11, 2000.
15. Tara Chand V, Ravindra K and Bala Prasad K. Exergy assessment of air film blade cooled combined power cycle plant. Int J Ambient Energy 2020; 41: 994–1006.
16. Tara CV, Ravindra K and Bala PK. Performance augmentation of combined cycle power plant under the control of differing open loop cooling techniques to the gas turbine blades. Int J Ambient Energy 2020.
17. Jordal K. Gas turbine cooling modeling - thermodynamic analysis and cycle simulations. Thesis, Lund University, 1999.
18. Jiang C and Chen H-p. Study on approximate calculation of cooling air allocation for gas turbine. In: 2009 Asia-Pacific power and energy engineering conference, Wuhan, China, March 27–31, 2009.
19. Yin F, Tiemstra FS and Rao AG. Development of a flexible turbine cooling prediction tool for preliminary design of gas turbines. J Eng Gas Turbines Power 2018; 140: 91201.
20. Yin F, Rao AG, Bhata, et al. Performance assessment of a multi-fuel hybrid engine for future aircraft. Aerosp Sci Technol 2018; 77: 217–227.
21. Shvets IT and Dyban EP. Air cooling of gas turbine parts. Kiev: Naukova dumka, 1974, p.488.
22. Li C and Liu J-J. A one-dimensional analytical method for turbine blade preliminary cooling design. In: Proceedings of the ASME Turbo Expo 2C V02CT39A027, Seoul, South Korea, June 13–17, 2016.
23. Li H-B, Gu C and Song Y. Through-flow calculation with a cooling model for cooled turbines. Proc IMechE, Part A: J Power and Energy 2015; 229: 862–875.
24. Li H and Gu C. Through flow calculations for convective cooled turbines In: Proceedings of the ASME Turbo Expo 2B, Dusseldorf, Germany, June 16–20, 2014.
25. Zyzon LT and Nesterenko VG. Designing of shrouded cooled blades for high-temperature and high-pressure turbines. Int Sci J 2018; 1: 84–90.
26. Kuz'michev VS and Trofimov AA. Design-point calculations of the main parameters of the aircraft gas turbines and compressors. Kuibyshev: Kuibyshev Aviation Institute, 1990, p.72.
27. Inozemtsev AA, Nikhamkin MA and Sandratskii VL. Fundamentals of gas turbine engines and power plants designing. Volume 2. Compressors. Combustion
chambers. Afterburners. Turbines. Exhaust devices. Moscow: Mashinostroenie, 2008, p.365.
28. https://helpiks.org/3-88101.html (accessed 22 April 2021).
29. Gritsenko EA, Danil’chenko VP, Lukachev SV, et al. Some issues of aviation gas turbine engines designing. Samara: SNTs RAN, 2002, p.527.
30. Pavlenko GV and Volov AG. Gasdynamic designing of axial gas turbine. Kharkov: National Aerospace University, 2007, p.76.
31. Kholschevnikov KV, Emin ON and Mitrokhin VT. Theory and calculations of aviation turbomachines. Moscow: Mashinostroenie, 1986, p.432.
32. Kulagin VV. Theory, calculations and designing of aircraft engines and power plants: fundamentals of theory of gas turbine engines. Working process and thermodynamic analysis. Volume 1. Joint operation of engine elements and its performance. Moscow: Mashinostroenie, 2002, p.616.
33. Grigoriev VA, Zhdanovskii AV and Kuzmichev VS. Parameters selection and thermodynamic calculations of aviation gas turbine engines. Samara: Samara State Aerospace University Publishing, 2009, p.202.
34. Derevyanko AV, Zhuravlev VA and Zikeev VV. Fundamentals of aviation turbines designing. Moscow: Mashinostroenie, 1988, p.328.
35. Potkin AN. Complex approach to designing high-temperature cooled gas turbines for reducing risks and development time. PhD thesis, P. A. Solovyov Rybinsk State Aviation Technical University, 2014, p.134.
36. Zhang J, Zhang S, Wang C, et al. Recent advances in film cooling enhancement: a review. Chin J Aeronaut 2020; 33: 1119–1136.
37. Kumar S and Singh O. Thermodynamic evaluation of gas/steam combined cycle performance with active controlled film cooling distributed generation and Alternative Energy J 2014; 29: 49–60.