Cooling Model Calibration in a Collaborative Turbine Preliminary Design Process Using the NASA Energy Efficient Engine
Part I: 0D Performance Modeling

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ABSTRACT

Under the NASA Energy Efficient Engine (E3) program, two high pressure turbines (HPTs) were separately developed and tested by General Electric (GE) and Pratt & Whitney (P&W). Despite the corresponding NASA E3 design reports and several subsequent publications related to these HPTs, there is still no uniform and consistent data base, leading to the absence of some essential parameters. Therefore, 0D performance models of the NASA E3 HPTs were generated based on the available literature. The performance results agree well with the literature data and will be presented. Furthermore, a well-known turbine cooling modeling approach is calibrated using the 0D performance models and further 1D turbine models, which were created in a collaborative process. This is crucial since the predicted coolant mass flows significantly affect the gas turbine efficiency. Based on the obtained calibration results, a simplified turbine cooling model is also derived and calibrated in this paper, being applicable for performance studies in the early phase of preliminary design. In order to quantify the error due to simplification, both the original and the simplified turbine cooling model are applied in two parametric studies.

INTRODUCTION

In the 1970s, the NASA Energy Efficient Engine (E3) program was started in response to the energy crisis and the sharp rise in fuel prices [1]. The main objective of the program was to develop fuel saving technologies for civil and military transport aircraft engines. General Electric (GE) and Pratt & Whitney (P&W) were each contracted to define a flight propulsion system (FPS) that fulfilled the goals of the NASA E3 program [2, 3]. Based on the respective FPS, GE and P&W separately developed and tested the required engine component technology. Subsequently, the research and test results of GE and P&W were published in a series of in-depth reports. In the field of turbine cooling, GE and P&W's design reports of the high pressure turbine (HPT) are important since they contain detailed information on blade designs and cooling systems as well as on the occurring heat transfer coefficients and blade temperatures [4, 5]. The relevance of these reports is also reflected in the fact that they are still cited today and used to validate cooling modeling approaches [6, 7]. Despite the abundance of information, the HPT reports have a significant disadvantage: the data were often published in the form of reduced or nondimensional quantities. This leads to the absence of some essential parameters, which can partially be reconstructed, but this is error prone. To the authors' knowledge, no publication exists to date that consistently presents all of the important data. Therefore, our objective is to model the HPTs of GE and P&W in order to provide a valid data base for all future work related to the NASA E3. In this paper, which is Part I of a collaborative series, 0D performance models of the NASA E3 HPTs are presented. These models were generated based on the available literature data. All relevant performance results will be attached in the full paper. In Part II [8], more detailed 1D turbine models of the NASA E3 HPTs are presented which were created using the 0D performance models as input.

Since the amount of turbine cooling air significantly affects the gas turbine efficiency, it is crucial to use appropriate models that predict the required coolant mass flows already in the early phase of preliminary design. Various cooling models exist in the literature, however, the modeling approach of Holland and Thake [9] has become well-established and has been referenced in other important work [10, 11]. By means of the Holland and Thake model, the airfoil coolant mass flows can be estimated row-by-row in the absence of a specific blade geometry or a detailed cooling system. For this purpose, several nondimensional cooling parameters are introduced, such as the cooling efficiency or the film cooling effectiveness, which are required as input. The quantification of these parameters is a challenging task since they significantly affect the predicted coolant mass flows. In order to facilitate the selection of suitable input parameter values and to provide reliable data, the Holland and Thake cooling model is calibrated in Part II [8]. Therefore, 1D turbine models of the NASA E3 HPTs are used. Based on the obtained calibration results, a simplification approach of the Holland and Thake model is presented in this paper. The resulting simplified turbine cooling model is also calibrated by means of the NASA E3 HPT models and can be used in 0D performance calculations to provide a valid prediction of turbine coolant mass flows in the early phase of preliminary design. Finally, the simplified turbine cooling model as well as the original Holland and Thake model are applied in two parametric studies in order to quantify the error due to simplification.

PERFORMANCE MODELING OF THE NASA E3 HPTs

The first step towards the calibration of the Holland and Thake cooling model [9] is the generation of 0D performance models based on the available literature data. For this purpose, the performance module of the framework GTlab (Gas Turbine Laboratory) is applied [12]. The created performance models of the NASA E3 HPTs are presented in Fig. 1 and Fig. 2. All performance results will be listed in the full paper, offering a valid data base for future work related to the NASA E3.

P&W's NASA E3 HPT

Fig. 1 illustrates the generated 0D performance model of P&W's one-stage NASA E3 HPT. This model includes a combustor, a secondary air system (SAS) and the high pressure turbine (HPT) itself. The HPT is connected through a shaft to a generator which consumes the turbine power. Air is provided by the SAS to cool the stator and rotor of the HPT. The assumptions and values used to create the performance model will be described in detail for each component in the full paper.

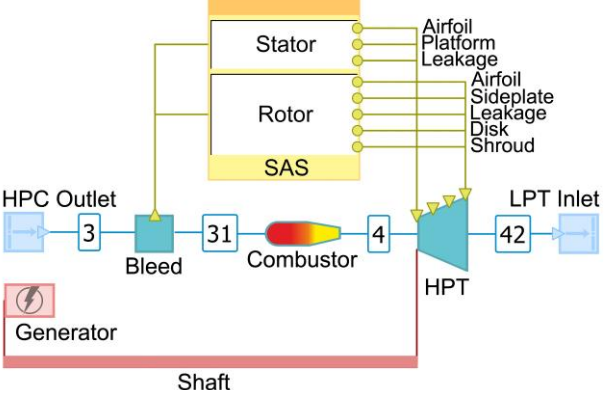

Fig. 1 0D performance model of P&W's one-stage NASA E3 HPT

The aim of the 0D performance model is to reproduce the available literature data of the NASA E3 HPT as accurately as possible. P&W's HPT design report [5] is used as main literary source. If data is missing, the P&W's FPS report [3] is considered. A comparison between the generated performance results and the literature data will be presented in the full paper. Important operating points are the aerodynamic design point (ADP), being defined by cruise conditions, and the off-design point takeoff (TO) which is used by P&W to dimension the turbine cooling requirements. The comparison shows that the created performance model reproduces well the available literature data of both operating points.

GE's NASA E3 HPT

In contrast to the previously presented performance model of P&W's one-stage NASA E3 HPT, the 0D performance model of GE's NASA E3 HPT is more complex since the HPT has two stages and a high pressure compressor (HPC) needs to be considered (see Fig. 2). Nevertheless, a similar setup as in Fig. 1 is pursued, but now the HPT is connected to the HPC and an additional turbine stage is considered in the SAS. The assumptions and values used to create the performance model will be described in detail for each component in the full paper.

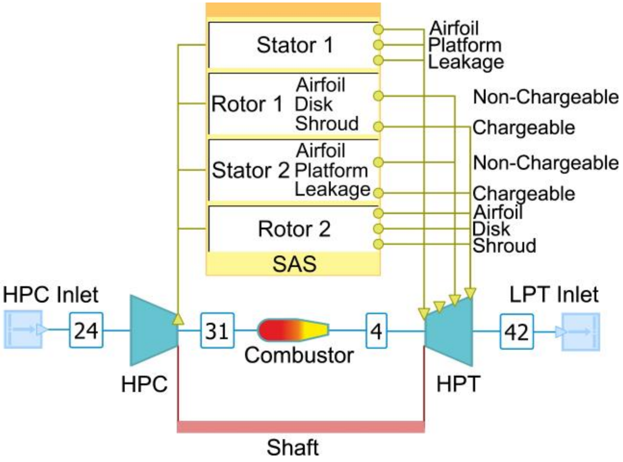

Fig. 2 0D performance model of GE's two-stage NASA E3 HPT

As before, the aim of the 0D performance model is to accurately reproduce the available literature data of the NASA E3 HPT. The HPT design report by GE [4] is the main literary source, whereas GE's FPS report [2] is only applied in case of missing data. Again, the comparison between the generated performance results and the literature data will be attached in the full paper. A good agreement with the available literature data is achieved here as well. Note that GE's NASA E3 HPT is designed at maximum climb (MCL). Relevant off-design points are takeoff (TO) as well as end of field at hot day conditions (EoF-HD) which is defined by a Mach number of 0.3 at sea level, an ambient temperature of 50 °C and a limited turbine rotor inlet temperature of 1616 K [4]. Since the highest coolant and hot gas temperatures occur at EoF-HD, this operating point is used by GE to dimension the turbine cooling requirements.

SIMPLIFIED TURBINE COOLING MODEL

The prediction of the required airfoil coolant mass flows of each blade row in the absence of specific blade geometries or detailed cooling systems is a challenging task in the early phase of preliminary design. Nevertheless, this is an important issue since coolant mass flows significantly affect the gas turbine efficiency. An appropriate approach for this purpose is the well-known cooling model of Holland and Thake [9]. This model and its application in a 1D turbine design process is described in detail in Part II of this collaborative series [8]. The essential equation for calculating the relative coolant mass flow $\dot{m}_c/\dot{m}_g$ of a blade row is as follows ($\dot{m}_g$ is the respective blade row inlet mass flow):

$$\frac{\dot{m}_c}{\dot{m}_g} = \frac{c_{p,g}}{c_{p,c}} \cdot \frac{A_b}{A_g} \cdot St_g \cdot HLP \cdot SF \tag{1}$$

$c_{p,g}/c_{p,c}$ is the ratio between the isobaric specific heat capacity of the hot gas and the coolant, A_b/A_g is defined as the ratio between the blade surface area and the hot gas throat area, St_g is the hot gas Stanton number and HLP is the heat load parameter. Since the modeling approach of Holland and Thake only considers the airfoil coolant mass flow, a scaling factor SF is used to provide sufficient cooling air for peripheral elements, such as end walls or discs. The heat load parameter HLP is a dimensionless measure of the airfoil cooling requirement and can be calculated by introducing several nondimensional cooling parameters as shown in Eq. (2).

$$HLP = \frac{\varepsilon_f(1-\eta_c)+\varepsilon_0(\varepsilon_f\eta_c-1)}{\eta_c(\varepsilon_0-1)(1+Bi_{coat})} \tag{2}$$

The cooling efficiency η_c, describing the heating of the cooling air within the blade, and the film cooling effectiveness ε_f, considering the protective effect of the cooling film, are input parameters in the Holland and Thake model and have to be quantified appropriately. Therefore, these parameters are calibrated in Part II [8] using 1D turbine models of the NASA E3 HPTs. In case of coated blades, the coating Biot number Bi_{coat} has to be included in Eq. (2) in order to account for the insulating effect of a thermal barrier coating (TBC). The cooling effectiveness ε_0 is defined in Eq. (3) and depends on the total hot gas temperature $T_{t,g}$, the total coolant temperature $T_{t,c}$ and the average blade temperature T_b which is limited by the material used.

$$\varepsilon_0 = \frac{T_{t,g}-T_b}{T_{t,g}-T_{t,c}} \tag{3}$$

Since the area ratio A_b/A_g and the hot gas Stanton number St_g in Eq. (1) are usually not known in the early phase of preliminary design, the cooling model of Holland and Thake cannot be applied in 0D performance studies. Therefore, the simplification of the model is proposed by introducing a factor $k = A_b/A_g \cdot St_g$ that is calibrated in this paper using the generated NASA E3 HPT models.

$$\frac{\dot{m}_c}{\dot{m}_g} = \frac{c_{p,g}}{c_{p,c}} \cdot k \cdot HLP \cdot SF \tag{4}$$

When calculating the heat load parameter *HLP* in performance analyses, it is recommended to apply calibrated nondimensional cooling parameters, except for the cooling effectiveness ε_0 which can be determined if a permissible average blade temperature is given. This is trivial for stators, but for rotors the total hot gas temperature $T_{t,g}$ in the relative coordinate system has to be considered in Eq. (3) which is usually not known in 0D performance studies. The temperature drop between absolute and relative coordinate system depends mainly on the rotor circumferential speed, but also on turbine stage design parameters, such as reaction and stage loading [13]. These parameters of the generated 1D NASA E3 HPT models [8] will be presented in the full paper as guidance for future preliminary design processes in which neither the reaction nor the stage loading is known.

COUPLED PERFORMANCE AND TURBINE MODELING

After deriving the simplified turbine cooling model (see Eq. (4)), which can be applied directly in performance studies, this section introduces a method to incorporate the original Holland and Thake cooling approach (see Eq. (1)) in 0D performance models. In addition to the performance module, the framework GTlab also includes a 1D turbine preliminary design tool called PrEDiCT [12]. The performance module and PrEDiCT can be connected via the Performance-PrEDiCT-Interface (PPI), enabling coupled 0D performance and 1D turbine modeling [12]. The PPI transfers the necessary input parameters, such as turbine inlet and coolant conditions, power requirements and shaft speeds, to PrEDiCT and executes it. Subsequently, PrEDiCT provides the calculated coolant mass flows and the turbine efficiency to the performance module which is also executed. This results in a closed loop that is iterated by the PPI until the turbine power deviation between the performance module and PrEDiCT is less than 0.001%. Since the original model of Holland and Thake is integrated in PrEDiCT for coolant flow calculations, the PPI enables the use of the original cooling approach in 0D performance models. However, this is far more complex than applying the simplified turbine cooling model. Note that the functionality of the PPI will be described and illustrated in more detail in the full paper.

RESULTS AND DISCUSSION

In this section, the previously derived simplified turbine cooling model is calibrated based on the generated NASA E3 HPT models. Additionally, the turbine inlet temperature and the coolant temperature are varied separately in two parametric studies in order to quantify the error due to simplification. Therefore, the simplified turbine cooling model (see Eq. (4)) is used directly in the 0D performance model, whereas the original Holland and Thake model (see Eq. (1)) is applied by means of the coupled performance and turbine modeling approach presented above. Assuming a constant cooling efficiency η_c and film cooling effectiveness ε_f, the cooling effectiveness ε_0 and thus the heat load parameter *HLP* can be calculated depending on the hot gas and coolant temperature (see Eq. (2) and Eq. (3)).

Calibration of the Simplified Turbine Cooling Model

Based on GE's and P&W's HPT design reports [4, 5], the relative coolant mass flow $\dot{m}_c/\dot{m}_g$ and the occurring average blade temperature T_b of each blade row can be reproduced. Thus, a calibration of the nondimensional cooling parameters of the Holland and Thake model [9] is possible which is the objective of this collaborative series. The cooling model calibration is crucial since the predicted coolant mass flows significantly affect the gas turbine efficiency.

As a valid calibration basis, 0D performance models (see Fig. 1 and Fig. 2) and more detailed 1D turbine models (see [8]) of the NASA E3 HPTs were generated using the available literature data. In Part II [8], all required input parameters of the original Holland and Thake equation are calibrated (see Eq. (1)). Since film-cooled blade rows require the cooling efficiency η_c and the film cooling effectiveness ε_f as input (see Eq. (2)), this is only possible if one of these two parameters is predefined. Therefore, the calibration is carried out for a film cooling effectiveness of 0.15, 0.20 and 0.25.

Using the results of [8] for a film cooling effectiveness of 0.20, the calibration of the previously derived simplified turbine cooling model (see Eq. (4)) is pursued in this paper in order to provide a suitable cooling prediction approach for performance studies in the early phase of preliminary design. Hence, the introduced *k*-factor has to be determined which is carried out in Table. 1 at takeoff conditions. When differentiating between stators and rotors, the *k*-factors are close together, although the NASA E3 HPT models were created independently based on the literature data. For stators, *k* is in the range of 0.023 to 0.029 (0.023 to 0.026 for first stage stators), whereas *k* is between 0.014 and 0.019 for rotors (0.017 and 0.019 for first stage rotors). The values of the area ratio A_b/A_g and the hot gas Stanton number St_g will be discussed in more detail in the full paper.

Table. 1 Calibration of the k-factor of the simplified turbine cooling model at takeoff conditions

Parameter	**P&W**		**GE**				**Source**
	Stage 1		Stage 1		Stage 2		
	Stator	Rotor	Stator	Rotor	Stator	Rotor	
η_c [-]	0.470	0.515	0.465	0.276	0.966	0.470	[8]
ε_f [-]*	0.200	0.200	0.200	0.200	0	0	
ε_0 [-]	0.616	0.500	0.649	0.450	0.250	0.188	
T_b [K]	1179	1122	1155	1179	1185	1131	
Bi_{coat} [-]	No TBC		No TBC				
HLP [-]	2.513	1.367	2.953	1.846	0.346	0.492	[8]
$c_{p,g}/c_{p,c}$ [-]	1.121	1.095	1.117	1.099	1.107	1.062	
A_b/A_g [-]	21.04	11.23	11.85	6.920	13.77	5.079	[8]
St_g [10^3]	1.243	1.713	1.942	2.524	2.104	2.845	[8]
SF [-]	1.345	1.876	1.530	1.850	1.230	2.320	[8]
$\dot{m}_c/\dot{m}_g$ [-]	0.099	0.054	0.116	0.066	0.014	0.018	
k [-]	0.026	0.019	0.023	0.017	0.029	0.014	

* predefined input parameter in [8]

Variation of Turbine Inlet Temperature

In the 0D performance model of P&W's one-stage NASA E3 HPT (see Fig. 1), the total turbine inlet temperature $T_{t,g,4}$ is varied by ±10 % at takeoff conditions. Fig. 3 shows the effect on the required coolant mass flows using the literature-based performance data (will be listed in the full paper) and the calibration results in Table. 1 as reference configuration. If the total turbine inlet temperature is increased, the stator coolant mass flow is underestimated by the simplified cooling model. The reason for this is the assumption of a constant *k*-factor which increases in the original cooling model due to a growing area ratio A_b/A_g and hot gas Stanton number St_g. Regarding rotor coolant mass flow, the same relations occur, but in this case the error due to a constant *k*-factor is compensated by an overestimated heat load parameter *HLP*. Hence, the predictions of both modeling approaches are quite similar. Since the simplified cooling model underestimates the stator coolant mass flow, the rotor inlet temperature and thus the cooling effectiveness ε_0 are greater than in the original cooling model. Consequently, the heat load parameter of the rotor is calculated too high in the simplified cooling model, leading to a pseudo increase in *k*-factor. If the total turbine inlet temperature is reduced, the opposite trends can be observed in Fig. 3.

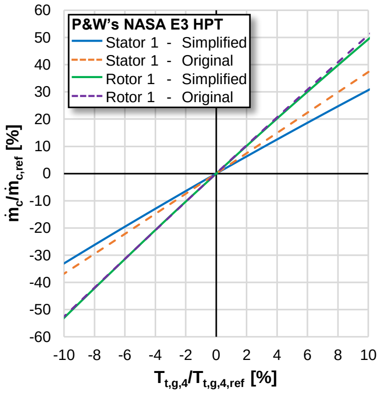

Fig. 3 Variation of turbine inlet temperature at takeoff conditions

Variation of Coolant Temperature

Retaining the combustor inlet temperature, the total coolant offtake temperature $T_{t,c,offtake}$ is varied by ±10 % at takeoff conditions in the 0D performance model of P&W's one-stage NASA E3 HPT (see Fig. 1). This leads to a variation in stator and rotor coolant temperature, the effect on the required coolant mass flows is presented in Fig. 4. Again, the literature-based performance data (will be listed in the full paper) and the calibration results in Table. 1 serve as reference configuration. Since the area ratio A_b/A_g and the hot gas Stanton number St_g of the stator and thus the k-factor are only affected marginally by the coolant temperature, the simplified and the original cooling model predict similar stator coolant mass flows. Consequently, the rotor inlet temperature is almost equal in both approaches. As for the stator, the discrepancy in the k-factor is also small for the rotor, so that the simplified and the original cooling model estimate similar rotor coolant mass flows.

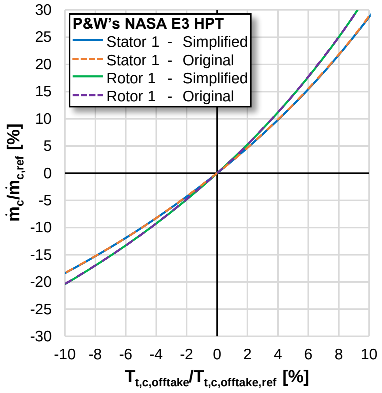

Fig. 4 Variation of coolant offtake temperature at takeoff conditions

CONCLUSION

As part of the NASA Energy Efficient Engine (E3) program, both General Electric (GE) and Pratt & Whitney (P&W) developed and tested a high pressure turbine (HPT). The corresponding HPT design reports are still cited today and used for validation, indicating their importance and popularity. Despite the abundance of information, some essential parameters are missing in the HPT reports, leading to a lack of a uniform and consistent data base. Therefore, 0D performance models of the NASA E3 HPTs were generated based on the available literature whose results agree well with the literature data. Thus, this paper provides a valid data base for all future work related to the NASA E3.

Based on a well-known cooling modeling approach, this paper also derives a simplified turbine cooling model which is suitable for performance studies in the early phase of preliminary design. Using the information on the relative coolant mass flows and the occurring blade temperatures provided in the NASA E3 HPT reports, the input parameters of the original and the simplified cooling model are calibrated for each blade row of the NASA E3 HPTs. The cooling model calibration is crucial since the calculated coolant mass flows significantly affect the gas turbine efficiency. Thus, the use of uncalibrated cooling models could lead to incorrect predictions and should be avoided. If a reliable calibrated reference point has been determined, either the original or the simplified cooling model can be applied. Both modeling approaches largely predict similar coolant mass flows for narrow parameter variations which is demonstrated in this paper by conducting two parametric studies. Since the simplified cooling model is more user-friendly and mostly provides comparable predictions to the original cooling model, it is particularly applicable for performance studies in the early phase of preliminary design, insofar as a reliable calibrated reference point is available.

REFERENCES

[1] Ciepluch, C. C., Davis, D. Y., and Gray, D. E., 1987, "Results of NASA's Energy Efficient Engine Program," *Journal of Propulsion and Power*, Vol. 3, No.6, pp.560-568.

[2] Davis, D. Y., and Stearns, E. M., 1985, "NASA Energy Efficient Engine - Flight Propulsion System Final Design and Analysis," *General Electric Report NASA CR-168219,* NASA Lewis Research Center, Cleveland, OH.

[3] Bisset, J. W., and Howe, D. C., 1983, "NASA Energy Efficient Engine - Flight Propulsion System Preliminary Analysis and Design Report - Final Update," *Pratt & Whitney Report NASA CR-174701,* NASA Lewis Research Center, Cleveland, OH.

[4] Halila, E. E., Lenahan, D. T., and Thomas, T. T., 1982, "NASA Energy Efficient Engine - High Pressure Turbine Test Hardware Detailed Design Report," *General Electric Report NASA CR-167955,* NASA Lewis Research Center, Cleveland, OH.

[5] Thulin, R. D., Howe, D. C., and Singer, I. D., 1982, "NASA Energy Efficient Engine - High-Pressure Turbine Detailed Design Report," *Pratt & Whitney Report NASA CR-165608,* NASA Lewis Research Center, Cleveland, OH.

[6] Chowdhury, N. H. K., Zirakzadeh, H., and Han, J. C., 2017, "A Predictive Model for Preliminary Gas Turbine Blade Cooling Analysis," *ASME Journal of Turbomachinery*, Vol. 139, No. 9.

[7] Yin, F., Tiemstra, F. S., and Rao, A. G., 2018, "Development of a Flexible Turbine Cooling Prediction Tool for Preliminary Design of Gas Turbines," *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 140, No. 9.

[8] Carvalho, F., Wehrel, P., Grunwitz, C., Schöffler, R., and Brakmann, R. G., 2023, "Cooling Model Calibration in a Collaborative Turbine Preliminary Design Process Using the NASA Energy Efficient Engine - Part II: 1D Turbine Modeling," *International Gas Turbine Congress 2023,* Kyoto, Japan.

[9] Holland, M. J., and Thake, T. F., 1980, "Rotor Blade Cooling in High Pressure Turbines," *Journal of Aircraft*, Vol. 17, No. 6, pp.412-418.

[10] Horlock, J. H., Watson, D. T., and Jones, T. V., 2001, "Limitations on Gas Turbine Performance Imposed by Large Turbine Cooling Flows," *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 123, No. 3, pp.487-494.

[11] Young, J. B., and Wilcock, R. C., 2002, "Modeling the Air-Cooled Gas Turbine: Part 2 - Coolant Flows and Losses," *ASME Journal of Turbomachinery*, Vol. 124, No. 2, pp.214-221.

[12] Wehrel, P., Schöffler, R., Grunwitz, C., Carvalho, F., Plohr, M., Häßy, J., and Petersen, A., 2023, "Performance and Emissions Benefits of Cooled Ceramic Matrix Composite Vanes for High Pressure Turbines," *ASME Turbo Expo 2023: Power for Land, Sea and Air,* Boston, MA.

[13] Dixon, S. L., and Halls, C. A., 2013, *Fluid Mechanics and Thermodynamics of Turbomachinery*, Elsevier Inc., Amsterdam, pp.119-168.