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## The Effect of Heat Transfer Coefficient Increase on Tip Clearance Control in H.P. Compressors in Gas Turbine Engine

**Godwin Ita Ekong**

Thermo-Fluid Mechanics Research  
Centre, University of Sussex, Brighton  
BN1 9QT, UK

**Christopher A. Long**

Thermo-Fluid Mechanics Research  
Centre, University of Sussex  
BN1 9QT, UK

**Peter R. N. Childs**

Dept. of Mech. Engineering  
Imperial College London  
South Kensington  
London, SW7 2AZ, UK

### ABSTRACT

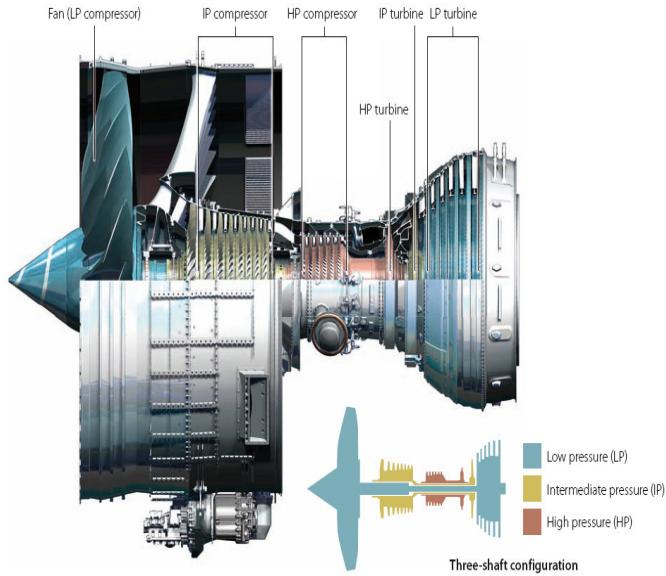
Compressor tip clearance for a gas turbine engine application is the radial gap between the stationary compressor casing and the rotating blades. The gap varies significantly during different operating conditions of the engine due to centrifugal forces on the rotor and differential thermal expansions in the discs and casing. The tip clearance in the axial flow compressor of modern commercial civil aero-engines is of significance in terms of both mechanical integrity and performance. In general, the clearance is of critical importance to civil airline operators and their customers alike because as the clearance between the compressor blade tips and the casing increases, the aerodynamic efficiency will decrease and therefore the specific fuel consumption and operating costs will increase. This paper reports on the development of a range of concepts and their evaluation for the reduction and control of tip clearance in H.P. compressors using an enhanced heat transfer coefficient approach. This would lead to improvement in cruise tip clearances. A test facility has been developed for the study at the University of Sussex, incorporating a rotor and an inner shaft scaled down from a Rolls-Royce Trent aero-engine to a ratio of 0.7:1 with a rotational speed of up to 10000 rpm. The idle and maximum take-off conditions in the square cycle correspond to in-cavity rotational Reynolds numbers of  $3.1 \times 10^6 \leq Re_\phi \leq 1.0 \times 10^7$ . The project involved

modelling of the experimental facilities, to demonstrate proof of concept. The analysis shows that increasing the thermal response of the high pressure compressor (HPC) drum of a gas turbine engine assembly will reduce the drum time constant, thereby reducing the re-slam characteristics of the drum causing a reduction in the cold build clearance (CBC), and hence the reduction in cruise clearance. A further reduction can be achieved by introducing radial inflow into the drum cavity to further increase the disc heat transfer coefficient in the cavity; hence a further reduction in disc drum time constant.

### INTRODUCTION

Tip clearance is the radial gap between the stationary compressor casing and the rotating blades. The gap varies significantly during different operating conditions of the engine due to centrifugal forces on the rotor and differential thermal expansions in the discs and casing. In general, as the clearance between the compressor blade tips and the casing increases, the aerodynamic efficiency will decrease and therefore the specific fuel consumption and operating costs will increase, and the clearance is therefore of critical importance to civil airline operators and their customers alike. In compressors, an efficient control scheme for the tip gap between the rotor blade and casing is necessary for engine stability; helping reduce surge

occurrences and the reduction in cruise clearance during the engine operating cycle.



**Figure 1: Trent 1000 jet engine illustrating the stages.**  
Courtesy of Rolls-Royce plc.

The objective of the investigations reported here are presentation of controlling the effect of heat transfer coefficient increase on tip clearance control in high pressure compressors (HPC), see Figure 1, during engine operations. The benefits will include control of surge occurrence and the reduction in specific fuel consumption. The focus of this paper is on the improvement of compressor tip clearance by increasing the heat transfer coefficient.

## NOMENCLATURE

A	Surface area [ $\text{m}^2$ ]
C	Specific heat capacity [ $\text{J/kg K}$ ]
h	Heat transfer coefficient [ $\text{W/m}^2\text{K}$ ]
T	Temperature [K]
V	Volume [ $\text{m}^3$ ]
$\rho$	Density [ $\text{kg /m}^3$ ]
$\tau$	Time constant [s]

## Background and review of previous work on tip clearance control schemes

Flow behaviour with axial throughflow and radial inflow in rotating cavities where two coaxial discs are rotating has been extensively discussed by Chew [1], Pincombe [2], Farthing [3], Tucker [4] and Long [5] Long et al [6]. For flow between two co-rotating compressor discs the flow can be modelled using a rotating cavity with a radial inflow approach (see Owen and Rogers [7]).

Various studies on the aerodynamic effect of tip clearance flows and clearance control techniques have been undertaken. The studies include a numerical investigation by Beheshti et al. [8] on the effect of casing treatment on performance and stability of transonic axial compressors who identified that casing treatment using slots and grooves increases the casing diameter of the area surrounding the rotor blade while the clearance remains constant and this reduces tip leakage flow through the end-wall zone and improves the compressor efficiency. Inoue et al. [9] examined experimentally the effect of tip clearance on the occurrence of rotating stall, in a low-speed aerofoil compressor stage with three axial gaps between the rotor and the front stator. The results indicate that the larger the gap the more possible the stall evolution. Lu et al. [10] identified in their work that the primary stall margin enhancement by casing treatment was made possible by the manipulation of tip clearance flow using slots and grooves in the shroud over the tips of compressor blades. Cassina et al. [11] carried out a numerical study on the suppression of flow instabilities in axial compressors using tip injection. This study demonstrated that tip injection effectively actuated the low momentum fluid at the rotor tip, optimised width to length ratio of the injector port and thereby improved the stability margin. Other studies are the numerical investigation of an active tip clearance control method based on cooling injection from the blade tip surface by Niu and Zang [12]. They concluded that injection location plays an important role in the redistribution of passage secondary flow. The closer to the pressure-side corner the injection is located, the more it reduces total pressure losses at cascade exit and that tip injection reduces the tip clearance mass flow to the level with half tip clearance height. Jothiprasad et al. [13] performed numerical simulations for the control of tip clearance flow in a low-speed axial compressor rotor with plasma actuation. This work investigated different dielectric barrier discharge (DBD) actuator configurations for affecting tip leakage flow and suppressing stall inception. The results showed that the actuation reduced end-wall losses by increasing the static pressure of tip gap flow emerging from the blade suction side. Further studies include the blade by blade tip clearance measurements in both compressor and turbine environments by Sheard [14] while an active stall control experiment with a magnetic bearing servo-actuator in the NASA Glenn high-speed single-stage compressor test facility was carried out by Spakovszky et al. [15] to stabilize rotating stall in axial compressors.

## Finite Element Analysis Code (SC03)

SC03 is a finite element analysis program developed by Rolls-Royce plc. This program is predominantly used for thermo-mechanical analysis which includes the prediction of component temperatures, component stresses, analysis of engine movement, deflections of axisymmetric or plane structures, and clearance optimisation. An axisymmetric model

was produced with the SC03 code. The boundary conditions within the SC03 program used in this study were Convecting Zones (CZ), Thermal Voids (VO), Thermal Streams (ST) and Thermal Ducts (DU). The selection of boundary conditions and the associated correlations used to define the heat transfer coefficient between the solid and fluid domains is essential for an accurate representation of the temperature distribution within the solid domain.

SC03 has inbuilt heat transfer coefficient correlations. The correlations employed in this study are the natural convection correlation associated with a plate and cylinder, used in voids in the cavities, and forced convection correlations for rotating flow, used in streams to model flow around the disc cobs and the cavities for radial inflow injection. Due to proprietary reasons, details of the inbuilt correlations used are not publicly available [17]. A full 2D thermo-mechanical casing and drum model of the T1000 engine using the Rolls-Royce finite element modeling analysis program SC03 was employed for this study. The T1000 gas turbine engine model has H.P. compressor with six stages.

A lumped parameter method is used to validate the SC03 model results. The lumped parameter model was developed to provide quick solutions that are approximately equivalent to the SC03 results with same input parameters. The lumped parameter scheme divides a thermal system into a number of distinct lumps and assumes that the temperature difference inside each lump is negligible. It is a simple and approximate procedure in which no spatial variation in temperature is allowed [18]. The change in temperature in such a system varies only with respect to time. The lumped heat capacity approach is limited to small sized bodies or high thermal conductivity material as with the case of the rotor/blade of an axial compressor in a gas turbine engine.

Time constants are a feature of the lumped system analysis for thermal systems. This is employed when objects cool or warm uniformly under the influence of convective cooling or warming as in the case of this study during acceleration and deceleration. Assuming a lumped mass approximation, the time constant is given in Equation 1.

$$\tau = \frac{\rho C_p V}{hA_s} \quad 1$$

For details on time constants and lumped system analysis for thermal systems, the reader is referred to [18], [19], [20], and [21].

The lumped parameter method shows that if the mass, volume and the area of the solid are constant, that increasing the heat transfer coefficient of the body will result in the reduction of the time constant and that decreasing the heat transfer coefficient of the body will result in the increased of the time constant. The aim of the study is to decrease the time constant of the drum by increasing the heat transfer coefficient of the systems thereby causing the drum to heat up faster hence narrowing down the large gap that existed at the beginning of

the engine transient operation between the casing and the blade. This would cause a reduction in the cruise clearance and a reduction in of clearance at surge point and hence reductions in the overall specific fuel consumption giving rise to higher engine efficiency.

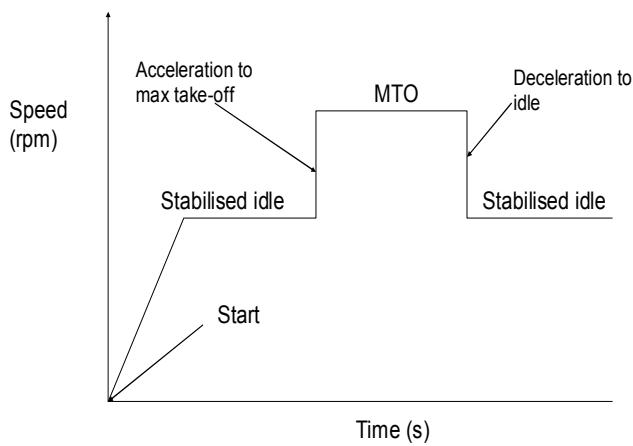
The lumped parameter model setup employed in this study starts with the environmental parameters (time vectors, temperatures and speed) setup which produces the square cycle for the analysis as shown in Figure 2. Upon successful completion of the environmental parameters setup, casing and drum displacements calculations setup are performed. This is followed by the generation of data for casing and drum total thermal growth as shown in Figure 3. The next process is to perform the closure behaviour setup follow by the generation of the closure behaviour data. Upon successful generation of the closure characteristics data, the results are analysed, summarised and compared to the SC03 model results as shown in Figure 4. The next process is to perform the clearance behaviour setup followed by the generation of the clearance behaviour data as shown in Figure 7.

## Methodology

The study was undertaken, using the SC03 models for the Trent 1000 drum and casing with an extended square cycle. The study presented here involves the effect of heat transfer coefficient increase on compressor tip clearance.

The study was performed by increasing the in built heat transfer coefficient in the cavity of the drum by an enhancement factor of 2, 4, 6 and 8. Three reference points were specified on each disc at various coordinates denoted as disc rim, mid disc and disc cob, from where the temperatures and displacements were measured. Average heat transfer coefficients were used to show the clearance reduction trends. The heat transfer coefficient is derived from correlations for natural convection from vertical plates or cylinders and forced convection from rotating flow. Natural convection for the upper surface of hot plates and lower surface of cool plates, and vertical plate or cylinder correlations were used in the cavity for heat transfer in the cavity void. A forced convection correlation for rotating flow was used for modelling streams modelling in the cavity region of the model for radial inflow and flows around the disc cob.

The cycle used is known as the square cycle as shown in Figure 2. The square cycle indicates the various phases during engine operation consisting of start, stabilization at idle, acceleration to max take-off (MTO), stabilization at max take-off (MTO), deceleration to idle and stabilization at idle.



**Figure 2: A typical engine square cycle.**

Two basic analyses are carried out to determine the compressor clearance during transients: Closure analysis; and Clearance analysis. For a given cycle, clearance depends on casing displacement and rotor displacement. The displacement of casing relative to rotor displacement is called closure. Clearance is the cold built clearance (CBC) value plus closure. Generally a decrease of time constant of the rotor and an increase of time constant of the casing is better for clearance and this is possible by increasing (decreasing) the heat transfer coefficient (htc) in the system. The post processing of the simulated data from the SC03 are performed using the Matlab code.

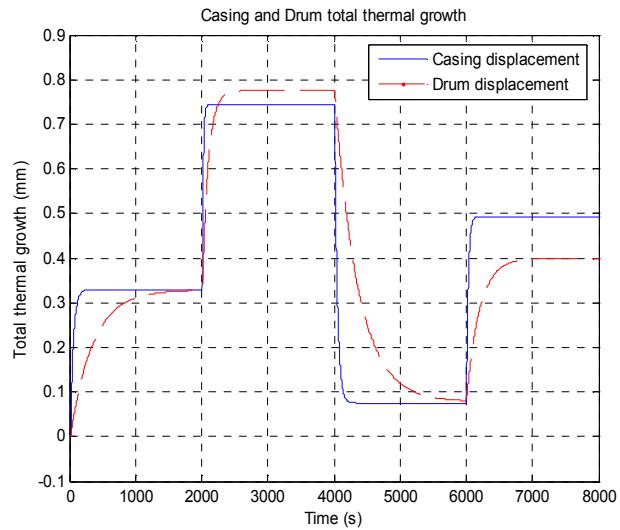
## Results

The quantitative effect of heat transfer coefficient increase on the closure and clearance behaviour of the high-pressure compressor stage is presented here in the form of:

- Thermal growth
- Time constant reduction
- Closure characteristics
- Clearance characteristics.

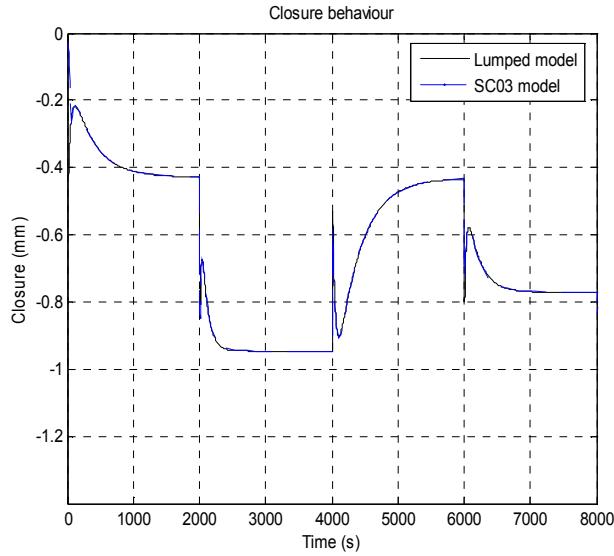
## Validation of SC03 model

In this section, results from the SC03 model against the lumped parameter closure behaviour for a single stage are presented as validation before using the model for the analysis. The closure behaviour of each stage is given by the relative expansion of the casing to the expansion of the drum as shown in Figure 3.



**Figure 3: The variation of total thermal growth of casing and drum with time over the extended square cycle for a single stage of the Trent 1000 casing and drum models.**

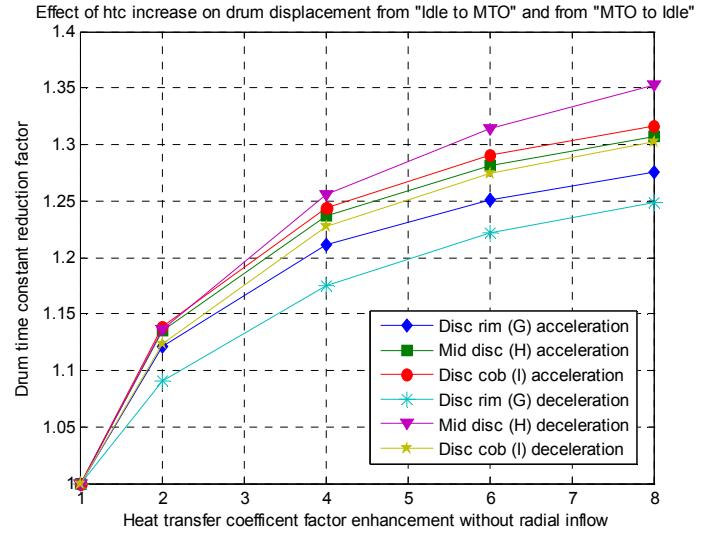
The closure is derived from the relative movement between the casing and the drum of a compressor stage which is the total thermal growth of casing and drum. This total thermal growth is obtained by the combined effect of the centrifugal growth (CF) with the transient thermal growths in the system. Figure 3 shows the variation of total thermal growth of the casing and drum with time over the extended square cycle for a stage in the Trent 1000 casing and drum models. The validation of the result from the lumped model with the results of the SC03 model is shown in Figure 4. The overall result of the validation process in Figure 4 shows that the results of the lumped model are in good agreement with the results (time constant and closure data) of the SC03 model.



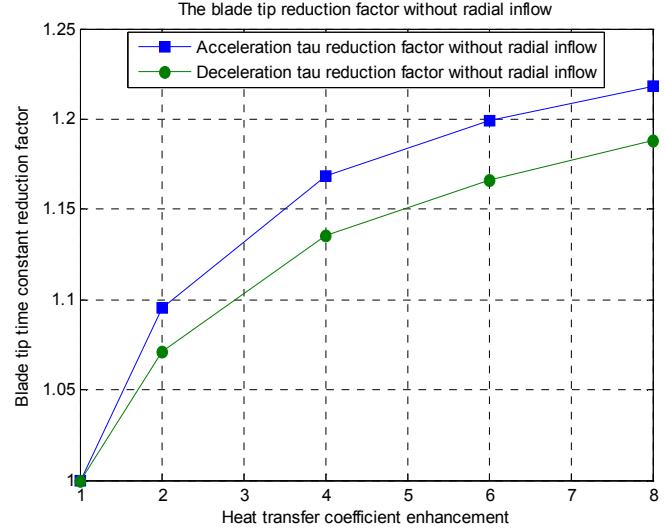
**Figure 4:** The Lumped model closure matched with SC03 closure over the extended square cycle for a single stage of Trent 1000 casing and drum models.

Analysis has been carried out to quantify the effect of increasing the heat transfer coefficient on the drum time constant, and hence the overall impact on clearance throughout the cycle during engine transient. The effect of heat transfer coefficient increase on displacement is presented in Figure 5. The blade time constant reduction factor due to heat transfer enhancement during engine transient from “Idle to MTO” and deceleration from “MTO to Idle” over a square cycle is shown in Figure 6. This illustrates a reduction as the enhancement is increased.

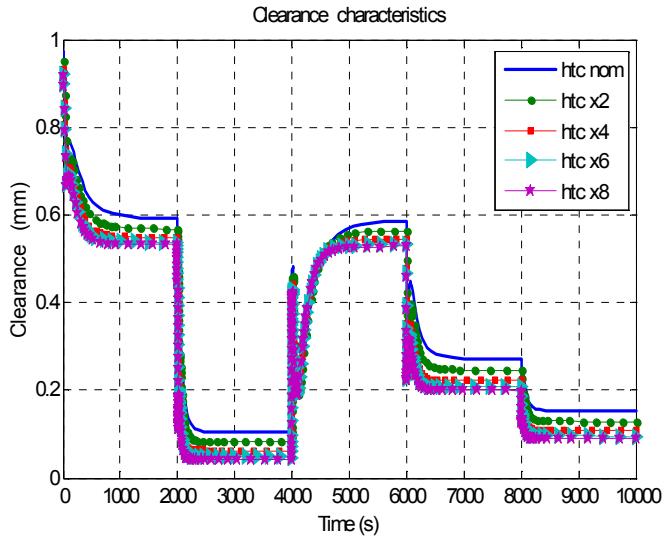
The overall impact of this effect can be seen in the clearance reduction throughout the entire cycle during engine transient as indicated in Figure 7. As the heat transfer coefficient is increased, the gap between the casing and the blade tip keeps reducing due to thermal expansion of the casing and the centrifugal acceleration associated with the drum. The slopes represent the rate at which the time constant is changing due to heat transfer enhancement; hence the slopes are a measure of the rate of heat transfer. As shown in Figure 5, continuous increase of the heat transfer coefficient will not guarantee a continuous time constant reduction because as time goes on, the rate of heat transfer decreases making the slopes of the lines less steep. This can be improved further by the introduction of radial inflow into the cavity to further enhance the heat transfer.



**Figure 5:** Displacement time constant reduction factor as a function of heat transfer coefficient during acceleration from “Idle to MTO” and deceleration from “MTO to Idle” over a square cycle for the Trent 1000 HP compressor stage at disc rim, mid disc and disc cob without radial inflow.



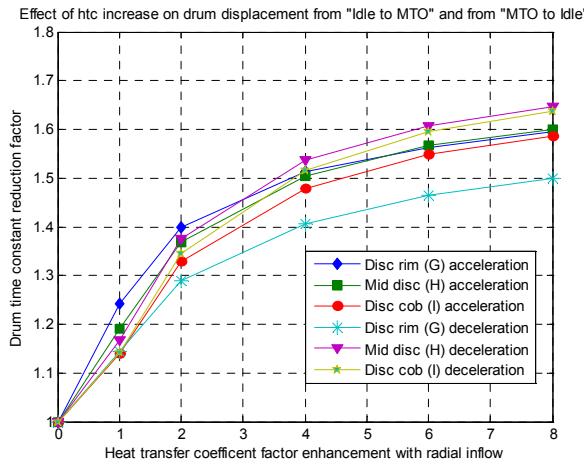
**Figure 6:** The variation of blade tip time constant reduction factor with heat transfer coefficient during acceleration from “Idle to MTO” and deceleration from “MTO to Idle” over a square cycle for the Trent 1000 HP compressor drum and casing models without radial inflow.



**Figure 7: The variation of clearance with time over the square cycle for the Trent 1000 HP compressor stage drum and casing model as a function of heat transfer coefficient without radial inflow.**

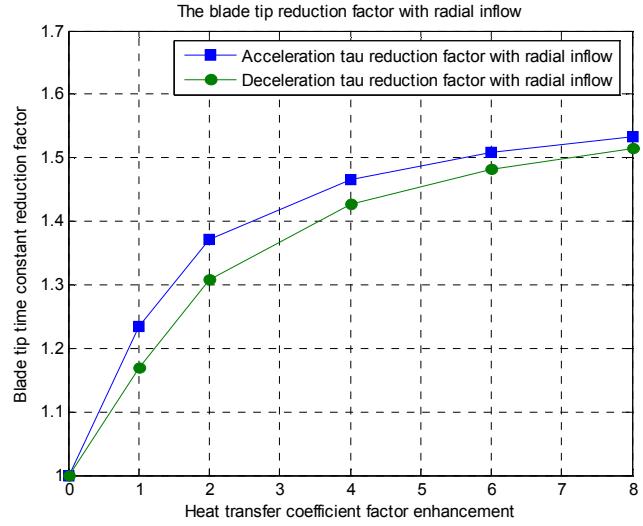
The analysis of a further enhancement of heat transfer in the cavity due to radial inflow is seen in the data presented in Figures 8 to 10. With radial inflow, the heat transfer coefficient is further increased, hence a further reduction in the gap between the casing and the blade tip.

The effect of introducing a small percentage of radial inflow on displacement is presented in Figure 8. Figure 8 has steeper slopes lines when compared to the gradients in Figure 5, hence a further increase in the heat transfer in the system leading to a further reduction clearance throughout the cycle.

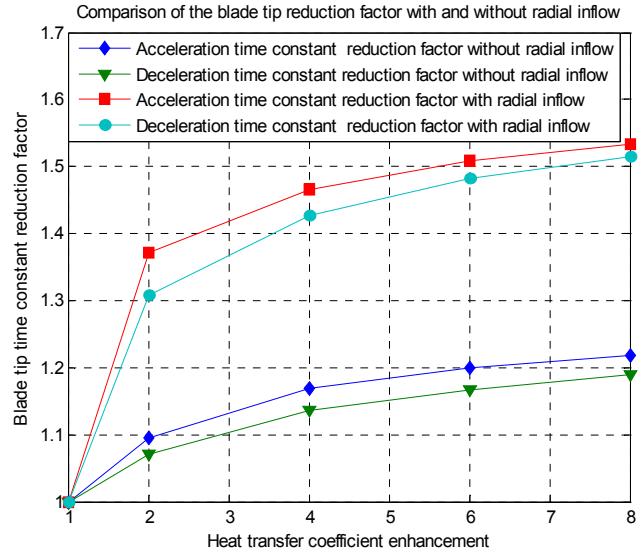


**Figure 8: Displacement time constant reduction factor as a function of heat transfer coefficient during acceleration from "Idle to MTO" and deceleration from "MTO to Idle" over a square cycle for the Trent 1000 HP compressor stage at disc rim, mid disc and disc cob with radial inflow.**

The blade time constant reduction factor due to radial inflow during engine transient from "Idle to MTO" and deceleration from "MTO to Idle" over a square cycle is shown in Figure 9. An indication of a further reduction in drum time constant is seen when comparing both analyses with and without radial inflow as shown in Figure 10.

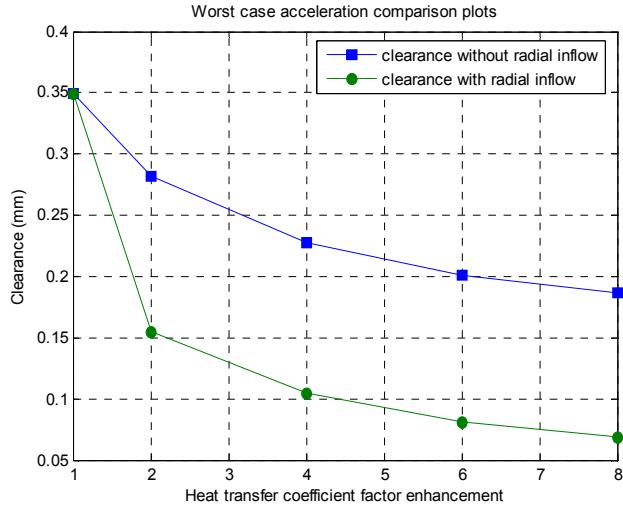


**Figure 9: The variation of blade tip time constant reduction factor with heat transfer coefficient during acceleration from "Idle to MTO" and deceleration from "MTO to Idle" over a square cycle for the Trent 1000 HP compressor drum and casing models with radial inflow.**

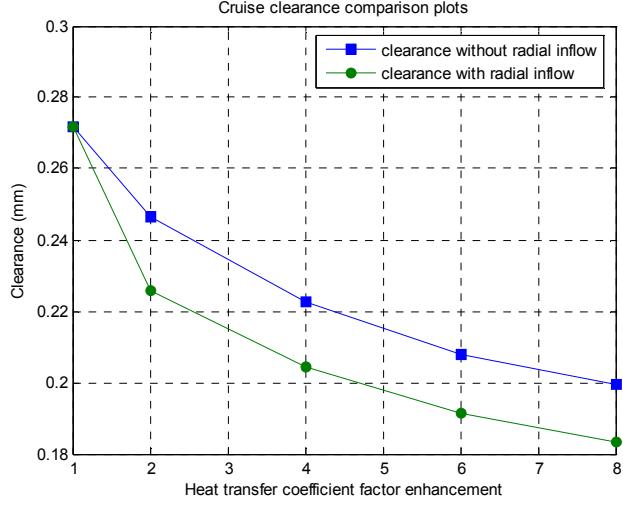


**Figure 10: The rotor blade tip time constant reduction factor comparison during acceleration from "Idle to MTO" and deceleration from "MTO to Idle" over a square cycle for the Trent 1000 HP compressor drum and casing models for the model without radial inflow and the model with radial inflow.**

The effects of heat transfer coefficient and the enhancement with a small radial inflow on tip clearance can be seen by considering the overall effect at the worst case acceleration and at cruise clearance as summarized graphically in Figure 11 and Figure 12 respectively.



**Figure 11: The comparison of the worst case acceleration clearance for Trent 1000 HP compressor stage drum and casing model as a function of heat transfer coefficient with radial inflow and without radial inflow.**



**Figure 12: The comparison of stabilised cruise clearance for Trent 1000 HP compressor stage drum and casing model as a function of heat transfer coefficient with radial inflow and without radial inflow.**

In summary, the effect of heat transfer coefficient on blade tip clearance are approximately 20%, 35%, 43% and 47% reductions in clearance at worst case acceleration and

approximately 10%, 18%, 24% and 27% reductions in clearance at stabilised cruise due to heat transfer coefficient increases factors of 2, 4, 6 and 8 respectively calculated from the baseline plot. This is further enhanced with a 6% percentage radial inflow which has a significant effect on blade tip clearance as indicated in Figures 11 and Figure 12. For details on the effect of radial inflow enhancement, the reader is referred to Ekong et al. [16].

## Conclusions

A lumped parameter method was used to validate the SC03 model results. The lumped parameter model was developed to provide quick solutions that are approximately equivalent to the SC03 results with same input parameters.

The analysis shows that increasing the thermal response of the high pressure compressor (HPC) drum of a gas turbine engine assembly will reduce the drum time constant, thereby reducing the re-slam characteristics of the drum causing a reduction in the cold build clearance (CBC), and hence the reduction in cruise clearance.

A further reduction can be achieved by introducing radial inflow into the drum cavity to further increase the disc heat transfer coefficient in the cavity; hence a further reduction in disc drum time constant.

Finally, this work shows the development of the concept of controlling tip clearance throughout the cycle in HP compressors of gas turbine engines by increasing the heat transfer coefficient in the cavity.

## ACKNOWLEDGMENTS

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