Quest Journals
Journal of Research in Mechanical Engineering
Volume 7 ~ Issue 8 (2021) pp: 18-25
ISSN(Online) : 2321-8185
www.questjournals.org

Research Paper

Modelling Of the Effect of Radial Inflow on the Fuel Consumption in a Gas Turbine Engine

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ABSTRACT

The Radial inflow is theintroduction of the bye-pass air from the compressor core flow into the drum cavity to improve heat transfer in the cavity. This will reduce the disc time constants, since they are found to depend on the heat transfer coefficient increase of the disc,hence, a reduction in the fuel consumption in a gas turbine engine during engine transient.This paper presents the 2-D modelling of the radial inflow process leading to a reduction in fuel consumption using a finite element analysis program. The results are presented in the form of a contour plot, time plot and a time constant reduction plots for a radial inflow quantity of 1.6%, 2%, 3%, 4% and 6%. The analysis of a 6% radial inflow indicates that with a 6% radial inflow, the heat transfer coefficient will be enhanced and is capable of reducing the disc time constant by approximately 44% during acceleration at high power and 39% during deceleration at low power. This is equivalent to an average time constant reduction factor of 2 during acceleration and 1.8 during deceleration. This will lead to an improved engine efficiency of 0.2% pointsand approximately 0.1% pointsreduction in the specific fuel consumption (SFC) of the engine, hence, a total saving of $16M per year in fuel costs for one airline can be achieved.

KEYWORD: *Modelling, Radial inflow, Fuel Consumption, Multiple Cavity rig, High Pressure compressor, Heat transfer, Time Constant.*

Received 14 August, 2021; Revised: 26 August, 2021; Accepted 28 August, 2021

I. INTRODUCTION

ThegasturbineisaTurbomachineryandabrandofaninternalcombustionengine.Areasofapplicationofgasturbinesinclude, butnotlimitedtothepropellingofanaircraft, trains, ships, electricalgenerators, pumps, gascompressors, andtanks.Hence, duetoitsvariousareasofapplication, thestudyofthefuelconsumptioninagasturbineengineisdesirable. In this study, a multiple cavity that is equivalent to the cavity of high-pressure compressor used in a typical a gas turbine engine was employed for the analysis. The analysis was to study the effect of heat transfer coefficient increased as it affects the fuel consumption during engine operation. Increasing the inbuilt heat transfer coefficient in the cavity and around the disc cob region would reduce the disc time constant. The reduction in disc time constant can be further enhanced by introducing radial inflow into the drum. The radial inflow which is the bleed air from the core flow will increase the heat transfer in the drum cavity hence improving the heat transfer coefficient. Two model namely the baseline model and a model with 6% radial inflow are used. The baseline model analysis indicates that, the continuous increase of the inbuilt heat transfer coefficient will not in a long term guarantee continuous reduction in disc time constant hence the need for a bleed air from the core flow. Hence, by introducing the radial inflow into cavity, the average temperature of the disc is raised.

II. REVIEW

Radomski (1982) carry out an investigation into the compressor clearance in high pressure compressor of a CF6 jet engine for National Aeronautics and Space Administration (NASA) and came to the conclusion that a 1mm (0.040 in) reduction in clearance would produce a normalized average clearance change of 0.78%. This gave a corresponding increase in the compressor efficiency by 0.78% and a reduction in specific fuel consumption (SFC) of the fan engine by 0.38%. A good control method that reduces blade tip clearances significantly in aerofoil compressors will lead to a significant increase in the on-wing life of commercial aircraft. This will bring about the reduction in engine instability, reductions in specific fuel consumption (SFC) thus saving fuel costs. As a 1% reduction in SFC across the then current fleet could save a total of $160M per year in fuel costs Lattime and Steinitz (2002), reduce air accident rate. It will also increase economic and environmental benefits to the public due to reduction in emissions (NO_x, CO_2), increased payload and mission range capabilities, reduction in pressure losses and the overall increase in engine efficiency. For aircraft fuel consumption – estimation and visualization, fuel efficiency of commercial aircraft, overview of historical and future trends, the performance of the gas turbine for power generation, gas turbine monitoring system and fuel economy Tradeoff, the reader is referred to works by Marcus Burziaff (2017), Peeter P. M.*et. al.* (2005), Linda Larsson (2014), MohdAldil Bin Zaini (2008), Ozmen, Teoman (2006) and Donald warren Mackenzie (2009.

III. METHODOLOGY

The method used include a 2D modelling of the High-pressure compressor using a finite element analysis program called the SC03(Rolls-Royce plc., 2004), along mathematical model using a MATLAB program.The Matlab programme was used for the post processing analysis of the results. The time constant analysis for four specified location on the upstream section of disc were obtained by evaluating the transient data using a first order model given by Equation 3.1.

$$T(t) = T_\infty + (T_0 - T_\infty)e^{\frac{-t}{\tau}} \qquad 3.1$$

where τ, is the time constant as given in Equation $\tau = \frac{mC}{hA}$ and $(T_0 - T_\infty) = \Delta T$, is the temperature change at each model point and t is time in seconds.The time constant is evaluated at the transients between the Idle and MTO during acceleration and MTO and Idle during deceleration in approximately 60 seconds. The results are presented in Sections 4.

The study was performed by running the baseline model first and the second analysis by introducing the radial inflow into the cavity. Temperatures from three reference model points and one model point from the disc cob on each disc at various coordinates were used for the analysis. The average heat transfer coefficient was used to show the clearance reduction trends in terms of disc time constant.
The results of the analysis performed using the MCR drum model are mostly presented in the form ofContour plots, Time plots andTime constant reduction graph, which are presented as Figures 3.1, 3.2 respectively, and the Time constant reduction graph which is the core concept in this paper is presented as Figure 3.3.

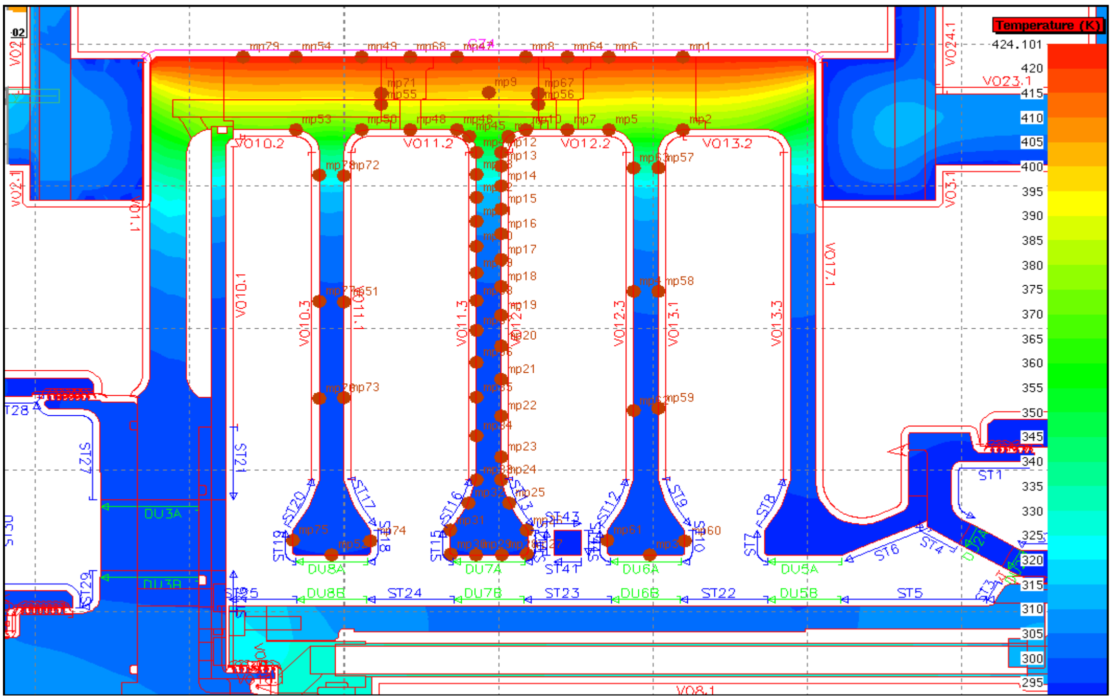

Figure 3.1: Temperature contour plots with a maximum rotational speed of 8000rpm, maximum take-off temperature of 381K.

The contour plots provide a qualitative understanding of the predicted temperature, stress, and distribution in and around a component.The contour plots of Figure 3.1show the temperature contour plots of the MCR drum baseline model with a bore temperature of 291K and the rim temperature of 425K. Another technique of presenting the analysis results is the time plot, which is capable of generating a graph of the result of a specific point on the model for the complete analysis cycle, as shown in Figure 3.2.

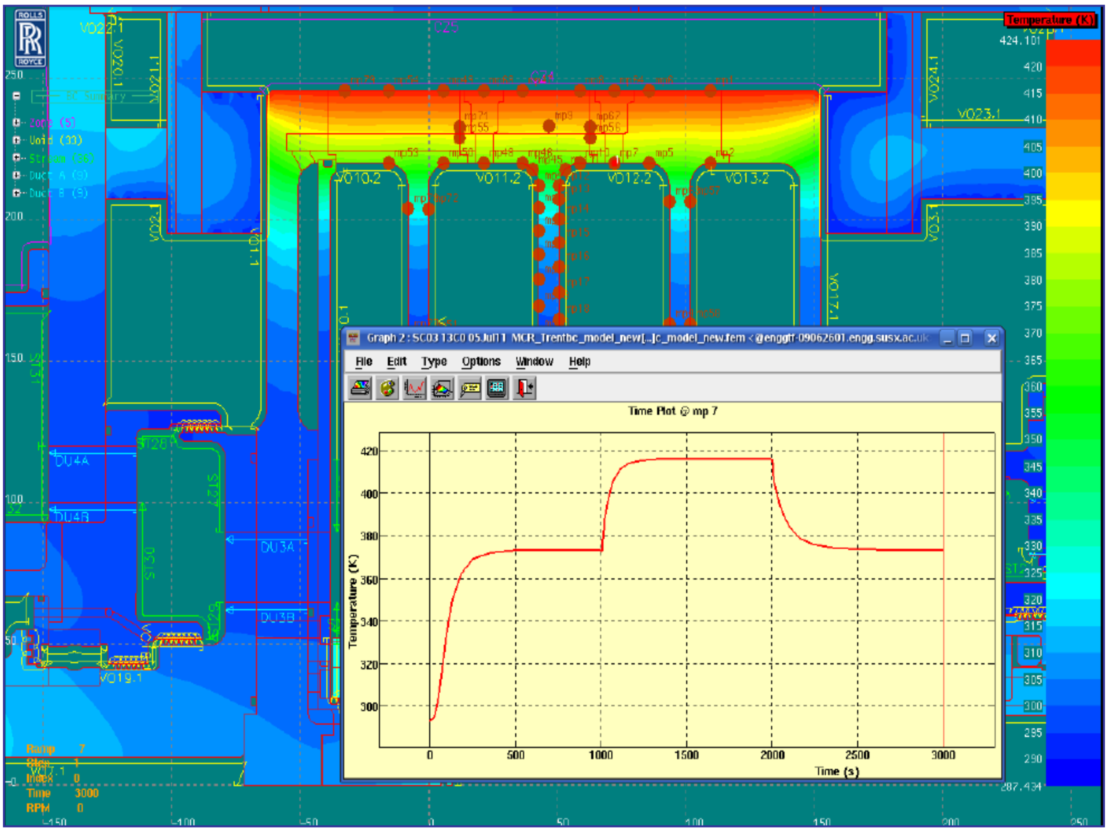

Figure 3.2: Time plot at model point 7

For the case without radial inflow, a simple heat transfer analysis is carried by increasing the inbuilt forced convective heat transfer coefficient in the streams around the disc cob and natural convective heat transfer coefficient in the voids in the cavity by an increased multiplicative factor of 1, 2, 4, 6 and 8. According to the relationship $\tau = \frac{mC}{hA}$,where the symbols retain their usual nomenclatures, an increase in the heat transfer coefficient will reduce the drum time constant.

IV. RESULT AND DISCUSSION

The study reported is a thermo-mechanical analysis run of the model and temperature measurements taken at the model point location on the MCR drum. The analysis in this paper is to show the reduction inthe disc time constant by increasing the heat transfer in the drum cavity, to ascertain its effect on the fuel consumption during engine transient. It will be recalled that the time constant, is the time required for a physical quantity to rise from zero to 63.2% of its final steady value or fall to 36.8% of its initial value. Hence, in this analysis, acceleration time constant is defined as the time required for the temperature to rise from the stabilised idle position at 1000s to 63.2% of its final steady value at 2000s during acceleration from Idle to maximum take-off (MTO). While deceleration time constant is defined as the time required for the temperature to fall from the stabilised maximum take-off (MTO) point at 2000s to 36.8% of its initial value at 3000s during deceleration from maximum take-off position to Idle (Ekong. G. I., 2014), when it varies with time as shown in Figure 3.3.

4.1Multiple Cavity Rig (MCR) results for model points MP12, MP18, MP22 and MP28 with radial inflow model

Figure 7.17 shows the variation of temperature with time for model with radial inflow at rotating-frame model pointMP12 for various radial inflow regimes. Tables 4.1, 4.2, 4.3 and 4.4 shows evidence of a significant time constant reduction with radial inflow model for different radial inflow percentageat rotating-frame model pointsMP12, MP18, MP22 and MP28 respectively, while Figures 4.1, 4.2, 4.3 and 4.4 shows the variation of temperature with time for a model with radial inflow at model point location MP12, MP18, MP22 and MP28 respectively on disc 2 upstream in the cavity 3 of the MCR. This variation, gives a temperature difference for acceleration and deceleration when calculated against the baseline temperature change for acceleration and deceleration respectively. It is at this temperature change that the time constant is obtained.

Table 4.1: Time constant reduction analysis for rotating-frame model point MP12 with radial inflow

Time constant reduction analysis for rotating-frame model point MP12 with radial inflow						
Flow regimes (% of bore mass flow)	**τ_{accel} (s)**	**% reduction from baseline model**	**Time constant reduction factor**	**τ_{decel}(s)**	**% reduction from baseline model**	**Time constant reduction factor**
Baseline	48.92	0	1	81.93	0	1
1.6	32.69	33.18	1.50	61.65	24.75	1.33
2	28.68	41.38	1.71	55.29	32.51	1.48
3	22.25	54.51	2.20	44.29	45.94	1.85
4	18.60	62.00	2.63	38.63	52.85	2.12
6	15.20	68.92	3.22	31.19	61.93	2.63

Radial inflow introduction into the cavity shows a significant reduction in disc time constant at MP12 by approximately 69% acceleration from Idle to MTO conditions and 62% during deceleration from MTO to Idle conditions when calculated against the baseline data. While the variation of temperature with time for a model with radial inflow at rotating-frame model pointMP12 for various radial inflow regimes is presented in Figure 4.1.

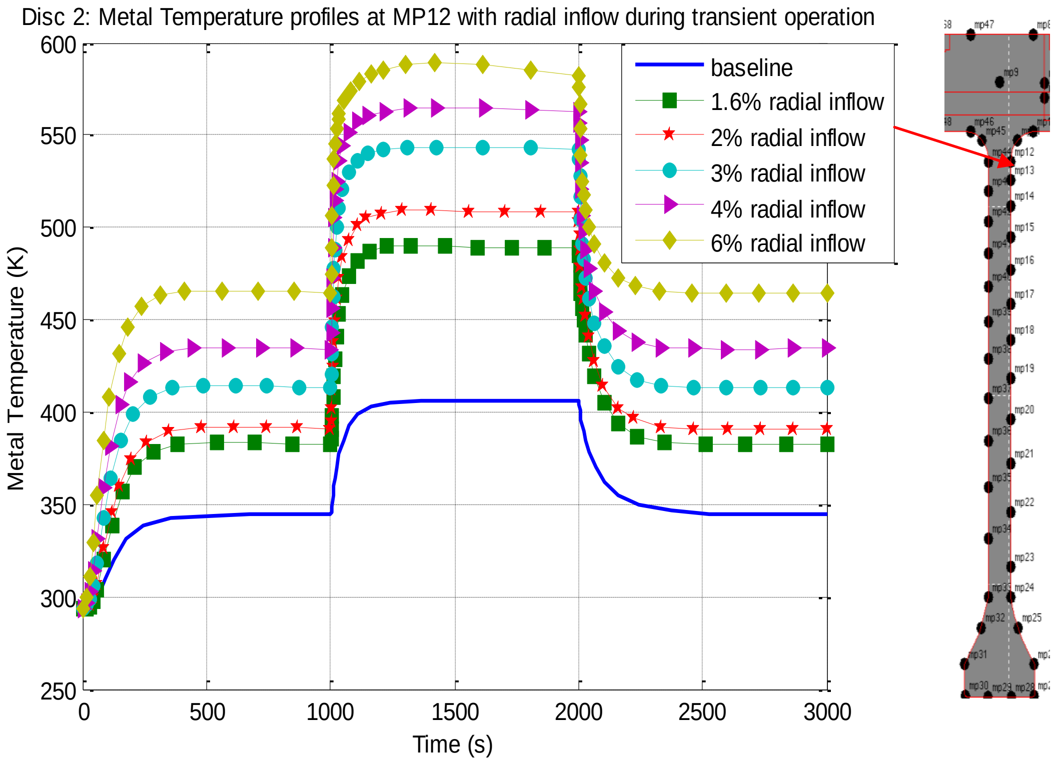

Figure 4.1: The variation of temperature with time for model with radial inflow at model point location MP12 on disc 2 upstream in cavity 3 of the MCR

Evidence of time constant reduction of the radial inflow model with different radial inflow percentage for rotating-frame model point MP18 is presented in Table 4.2. The disc time constant at MP18 with radial inflow is reduced significantly by approximately 36% during acceleration from Idle to MTO conditions and

33% during deceleration from MTO to Idle conditions with 6% radial inflow calculated against the baseline data.While Figure 4.2indicate the variation of temperature with time for model with radial inflow at rotating-frame model pointMP18 for various radial inflow regimes.

Table 4.2: Time constant reduction analysis for rotating-frame model point MP18 with radial inflow

Time constant reduction analysis for rotating-frame model point MP18 with radial inflow						
Flow regimes (% of bore mass flow)	**τ_{accel} (s)**	**% reduction from baseline model**	**Time constant reduction factor**	**τ_{decel}(s)**	**% reduction from baseline model**	**Time constant reduction factor**
Baseline	35.34	0	1	97.78	0	1
1.6	32.70	7.47	1.08	87.96	10.04	1.11
2	32.72	7.41	1.08	86.68	11.35	1.13
3	30.20	14.57	1.17	82.50	15.63	1.19
4	26.93	23.80	1.31	76.12	22.15	1.29
6	22.77	35.56	1.55	65.67	32.84	1.50

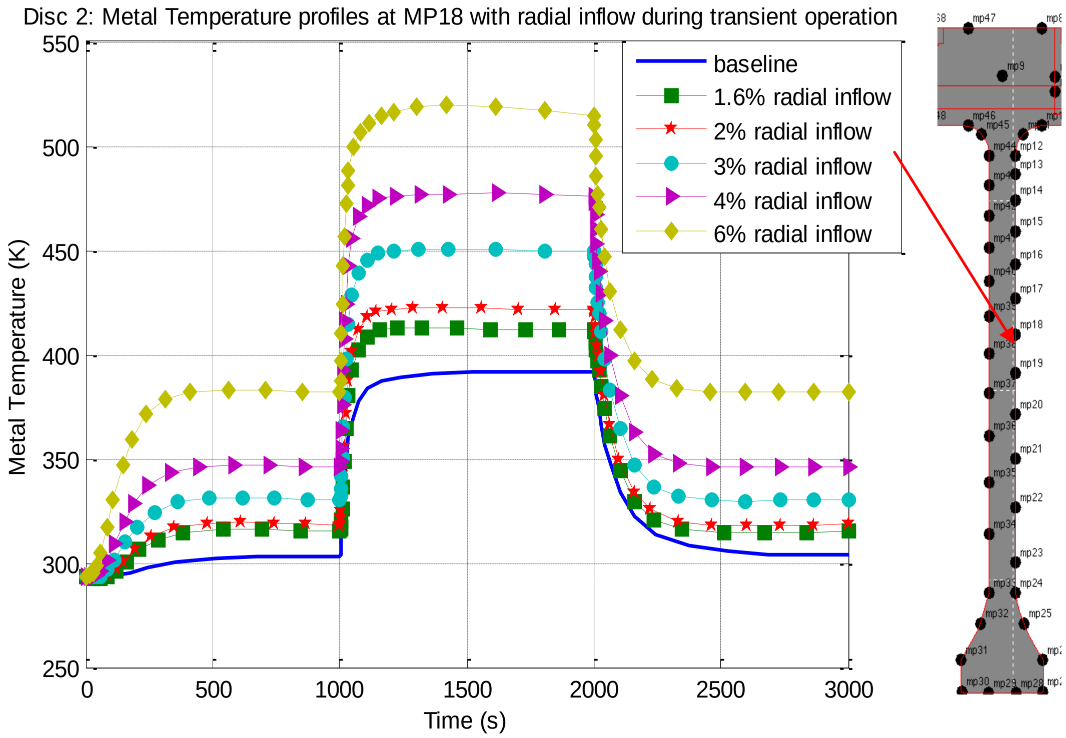

Figure 4.2: The variation of temperature with time for model with radial inflow at model point location MP18 on disc 2 upstream in cavity 3 of the MCR with increase in radial inflow

Table 4.3 shows proof of time constant reduction of the radial inflow model with different radial inflow regimes in the form percentage reduction and time constant reduction factor for rotating-frame model point MP22. The radial inflow model disc time constant at MP22 is reduced by approximately 27% during acceleration from IDLE to MTO conditions and 22% during deceleration from MTO to IDLE conditions with 6% radial inflow calculated against the baseline data.

Table 4.3: Time reduction analysis for rotating-frame model point MP22 with radial inflow

Time constant reduction analysis for rotating-frame model point MP22 with radial inflow						
Flow regimes (% of bore mass flow)	**τ_{accel} (s)**	**% reduction from baseline model**	**Time constant reduction factor**	**τ_{decel}(s)**	**% reduction from baseline model**	**Time constant reduction factor**
Baseline	37.82	0	1	120.14	0	1
1.6	35.51	6.10	1.07	110.50	8.023	1.09
2	36.25	4.14	1.04	110.88	7.71	1.08
3	34.93	7.63	1.08	109.82	8.60	1.10

4	32.90	13.00	1.15	104.10	13.36	1.15
6	27.70	26.76	1.37	93.64	22.06	1.28

Figure 4.3 shows the variation of temperature with time for a model with radial inflow at rotating-frame model pointMP22 for various radial inflow regimes.

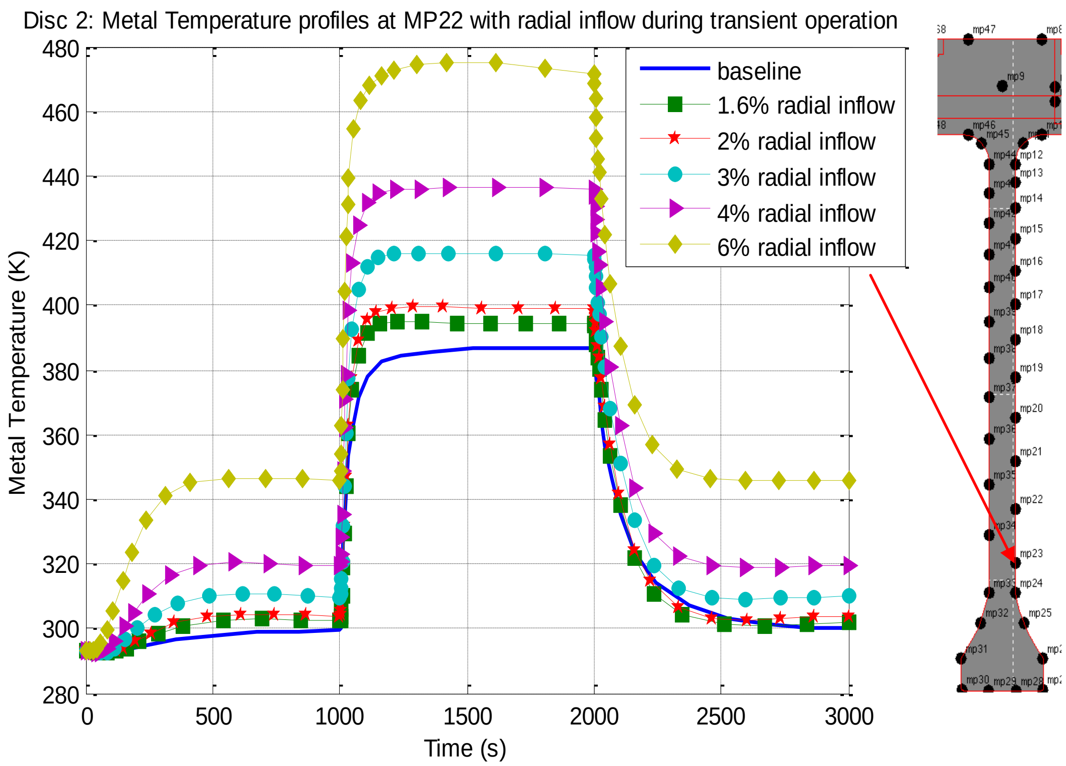

Figure 4.3: The variation of temperature with time for model with radial inflow at model point location MP22 on disc 2 upstream in cavity 3 of the MCR with increase in radial inflow.

The indication of time constant analysis in the disc cob region for the model with radial inflow at rotating-frame model point MP28 is accessible in Table 4.4 in the form percentage reduction and time constant reduction factor.

Table 4.4: Time reduction analysis for rotating-frame model point MP28 with radial inflow

Time constant reduction analysis for rotating-frame model point MP28 with radial inflow						
Flow regimes (% of bore mass flow)	**τ_{accel} (s)**	**% reduction from baseline model**	**Time constant reduction factor**	**τ_{decel}(s)**	**% reduction from baseline model**	**Time constant reduction factor**
Baseline	34.27	0	1	158.16	0	1
1.6	45.30	-32.14	0.76	190.36	-20.36	0.83
2	45.62	-33.12	0.75	190.75	-20.61	0.83
3	46.44	-35.51	0.74	196.20	-24.06	0.81
4	46.80	-36.57	0.73	198.77	-25.68	0.80
6	46.65	-36.12	0.74	198.76	-25.67	0.80

Figure 4.4 shows the variation of temperature with time for a model with radial inflow at rotating-frame model pointMP28 as a function of heat transfer coefficient. With radial inflow, the heat transfer around the disc cob is less when compared to other parts of the disc as such no significant reduction in disc time constant in the cob region as expected. The introduction of radial inflow into the cavity does not show significant increase the heat transfer (has less effect) around the disc cob region. This is so because the disc cob region comes into contact with the bore flow more than other part of the disc during engine operation.

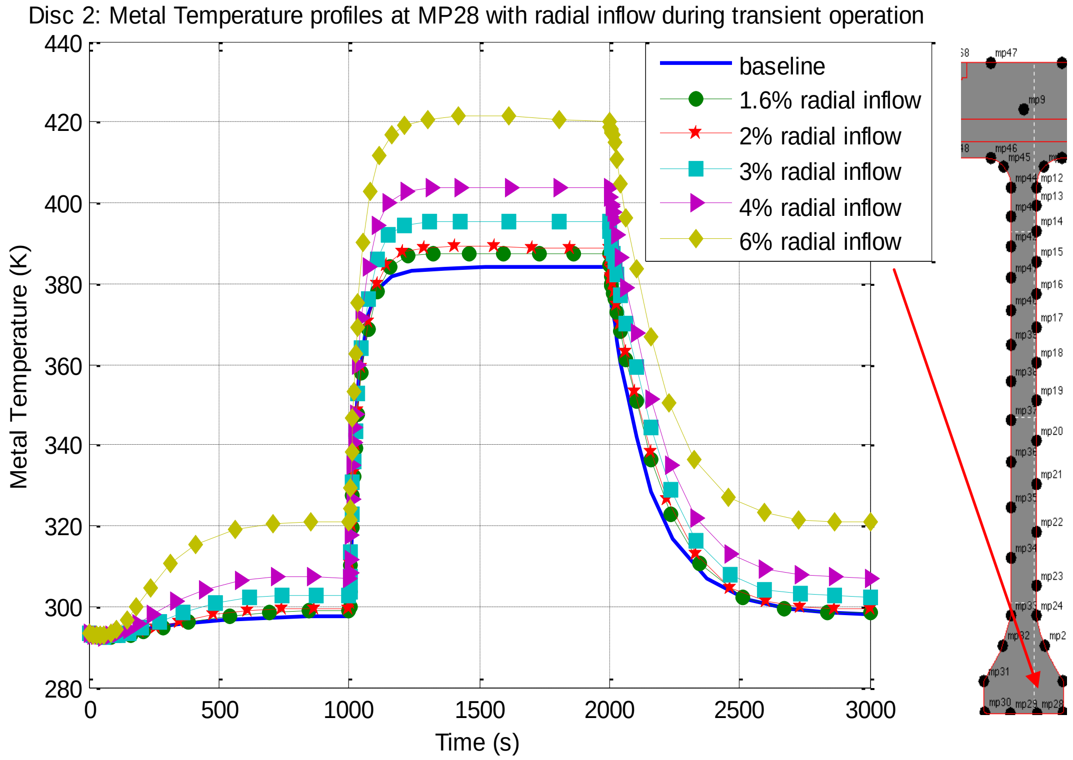

Figure 4.4: The variation of temperature with time for model with radial inflow at model point location MP28 on disc 2 upstream in cavity 3 of the MCR with increase in radial inflow.

4.2. Discussion

The time constant reduction factor as a function of radial inflow during acceleration from “Idle to MTO” and deceleration from “MTO to Idle” over a square cycle for model points MP12, MP18, MP22 and MP28 on disc 2 upstream of the MCR drum were presented. The results for a 6% radial inflow on the the disc time constant at MP12, MP18, MP22 and the disc cob model point MP28 has time constant reduction factor of approximately 3.22, 1.31, 1.37 and 0.74 respectively during acceleration from Idle to MTO conditions. This is equivalent to approximately 69%, 36%, and 27% reduction with a 36% increase for the disc cob respectively calculated against the baseline data.And approximately 2.63, 1.50, 1.28 and 0.80 which is equivalent to approximately 62%, 33%, and 22% reduction with a 26% increase for the disc cob respectively, during deceleration from MTO to Idle conditions with 6% radial inflow calculated against the baseline data.

The analysis indicates that with the introduction of the radial inflow into cavity 3, the average temperature of the disc 2 is raised relative to the baseline model and there is also a reduction in temperature gradient along the disc downward from the shroud. The analysis with radial inflow in cavity 3 shows a possible reduction in disc 2 time constant by approximately 69%, 36% and 27% during acceleration and 62%, 33% and 22% during deceleration with 6% radial inflow at MP12, MP18 and MP22 respectively on disc 2 upstream calculated against the baseline nominal data. This is equivalent to a time constant reduction of 3.22, 1.31 and 1.37 during acceleration and 2.63, 1.50 and 1.28 during deceleration from the baseline model for model points MP12, MP18 and MP22 respectively. Taking an average of the time constant reduction values for model points (MP12, MP18 and MP22) along the disc, it shows that with 6% radial inflow, the disc time constant may be reduce by approximately 2.0 during acceleration and 1.80 during deceleration. Finally, the concept of disc time constant reduction using the radial inflow works as anticipated. With the quantity of radial inflow employed in the analysis, there is an evident and significant reduction in the disc time constant. The 2-D modelling results shows that 6% (of bore flow) radial inflow is capable of reducing the disc time constant by approximately 44% during acceleration at high power and 39% during deceleration at low power. This is equivalent to a time constant reduction factors of 2 during acceleration and 1.8 during deceleration, hence an improvement of the efficiency by 0.2% points leading to the reduction of the cruise clearance by 0.22mm. Applying ideas from Radomski (1982) and Lattime and Steinitz (2002), this 0.22mm would give a corresponding increase in compressor efficiency by 0.2% points and the specific fuel consumption (SFC) of the engine would be reduced by approximately 0.1% points and this could save a total of $16M per year in fuel costs for one airline.

V. CONCLUSION

The 2-D modelling of the radial inflow process leading to a reduction in fuel consumption using a finite element analysis program was performed. The results of the disc time constant reduction plots for a radial inflow quantity of 1.6%, 2%, 3%, 4% and 6% indicates a reduction in disc time constant with the introduction of the radial inflow. The 2-D modelling results shows that 6% (of bore flow) radial inflow is capable of reducing the disc time constant by approximately 44% during acceleration at high power and 39% during deceleration at low power. This is equivalent to a time constant reduction factor of 2 during acceleration and 1.8 during deceleration. This will improve the efficiency by 0.2% points. The cruise clearance will be reduced by 0.22mm. This reduction of cruise clearance by 0.22mm would give a corresponding increase in compressor efficiency by 0.2% points and the specific fuel consumption (SFC) of the engine would be reduced by approximately 0.1% points. This reduction in the specific fuel consumption of the engine could save a total of $16M per year in fuel costs for one airline. Hence, from the analysis, the concept of disc time constant reduction using the radial inflow works as anticipated. Therefore, with the quantity of radial inflow employed in the analysis, there is an evident and significant reduction in the disc time constant, hence the reduction in tip clearance H.P. compressor during engine transient and consequently, a reduction in the specific fuel consumption (SFC) of the gas turbine engine.

ACKNOWLEDGMENTS

I acknowledged my supervisors during my research years at Thermo-Fluid Mechanics Research Centre, University of Sussex, Brighton, BN1 9QT, United Kingdom for their training and encouragement throughout my years at University of Sussex. Thanks to Rolls-Royce Plc for giving me the opportunity to do a research with this highly respectable company in the world and to be involved in the New Aero Core Concept (NEWAC), a European Union (EU) Framework 6 programme.

REFERENCES

[1]. Radomski, M. A. (1982) *High pressure compressor clearance investigation.* CF6 Jet Engine Diagnostics Program. National Aeronautics and Space Administration (NASA). NASA CR-165580.

[2]. Lattime, S. B. &Steinetz, B. M. (2002) *Turbine Engine Clearance Control Systems: Current Practices and Future Directions.* National Aeronautics and Space Administration (NASA). NASA/TM—2002-211794.

[3]. Marcus Burziaff (2017) Aircraft Fuel Consumption – Estimation and visualization, Faculty of Engineering and computer science, Department of Automotive and Aeronautical Engineering, Hamburg University of Applied Science.

[4]. Peeter P. M, Middel, J &Hoolhorst A. (2005) A Fuel efficiency of commercial aircraft and overview of historical and future trends.

[5]. Linda Larsson (2014) Aircraft fuel consumption can be reduced by 15 per cent Chalmers University of Technology.

[6]. MohdAldil Bin Zaini (2008) *The study of the performance of the gas turbine for power generation* B.Eng thesis (Gas Technology), University of Malaysia Pahang (UMP).

[7]. Ozmen, Teoman (2006) Gas Turbine Monitoring System,a thesis inAerospace Engineering to the Graduate school of Natural and Applied School of Natural and Applied Sciences of Middle East Technical University.

[8]. Donald warren Mackenzie (2009) *Trends and Drivers of the Performance -fuel economy Tradeoff in New Automobiles,* MSC thesis, Massachusetts institute of Technology.

[9]. Rolls-Royce plc. (2004) SC03 Thermo-Mechanics Quality System Rolls-Royce. capability Intranet.

[10]. Ekong. G. I. (2014). *Tip Clearance Control Concepts in Gas Turbine H.P Compressors.* D.Phil. Thesis, School of Engineering, University of Sussex, UK.