Quest Journals
Journal of Research in Mechanical Engineering
Volume 7 ~ Issue 8 (2021) pp: 07-17
ISSN(Online) : 2321-8185
www.questjournals.org

Research Paper

The Validation of a Multiple Cavity Rig (MCR) Model

Ekong, Godwin I.
Department of Mechanical Engineering Akwa Ibom State University (AKSU) and A Former Researcher, Rolls-Royce supported University Research Centre for Aero-Thermal Systems and Thermo-Fluid Mechanics Research Centre, University of Sussex, Brighton, BN1 9QT, UK.

Abstract
This paper presents the validation of the multiple cavity of a typical high pressure compressor simulated with real engine representative data.A multiple cavity rig is used to study the effect of the flow field in a heated rotating cavity with axial throughflow and radial inflow as well as their effect on tip clearance in high pressure compressor during engine transient.The basic parameters relevant to rotating cavities, the fluid dynamics and heat transfer of rotating flows are presented.The basic dimensionless (non- dimensional)flow parameters relevant to the rotating cavities with axial throughflow and radial inflow which characterising the flow conditions within a rotating system such as Reynolds number Re_{ϕ}, *axial Reynolds number* Re_{z}, *Rossby number* Ro_{z} *and the Grashof number Gr were matched to the multiple cavity rig conditions.The validation of the SC03 model*
with the mathematical model was performed and found to be in good agreement.

Keyword: *Validation, Multiple cavity rig, High Pressure compressor, Heat transfer, Flow parameter, mathematical model.*

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

I. INTRODUCTION

Validation is a process of verifying that a model is a correct representation of the process or system for which it is proposed. This is achieved if the predictions from the model are in good agreement with the experimental observations or mathematical model.In this study, it is performed by comparing the values of parameters of the model with values obtainable independently from a mathematical model from a MATLAB program. In the high pressure compressor cavity such as the multiple cavity employed in this work, it is performed by evaluating the predicted and measured temperatures to make certain that the thermal behaviour of the model reproduces the measured characteristics at transient and steady state conditions of the engine. According to Monico and Chew (1993), in some cases, it may be possible that the modelling assumptions used may not accurately represent some of the physical processes; as such, a mathematical method would be preferable for use in the matching process.The multiple cavity rig (MCR) model used in this study is found in the University of Sussex, United Kingdom. It represents the internal set-up of a high pressure compressor where the rotor and inner shaft of the rig were scaled down from a Rolls Royce Trent aero-engine to a ratio of 0.7:1. The rig is to simulate the internal air system flows within a High Pressure (HP) compressor where air, extracted from the Intermediate Pressure (IP) compressor and predestined for the Low Pressure (LP) turbine discs and seals, flows axially through the annular passage between the HP compressor discs bores and the enclosed IP drive shaft.

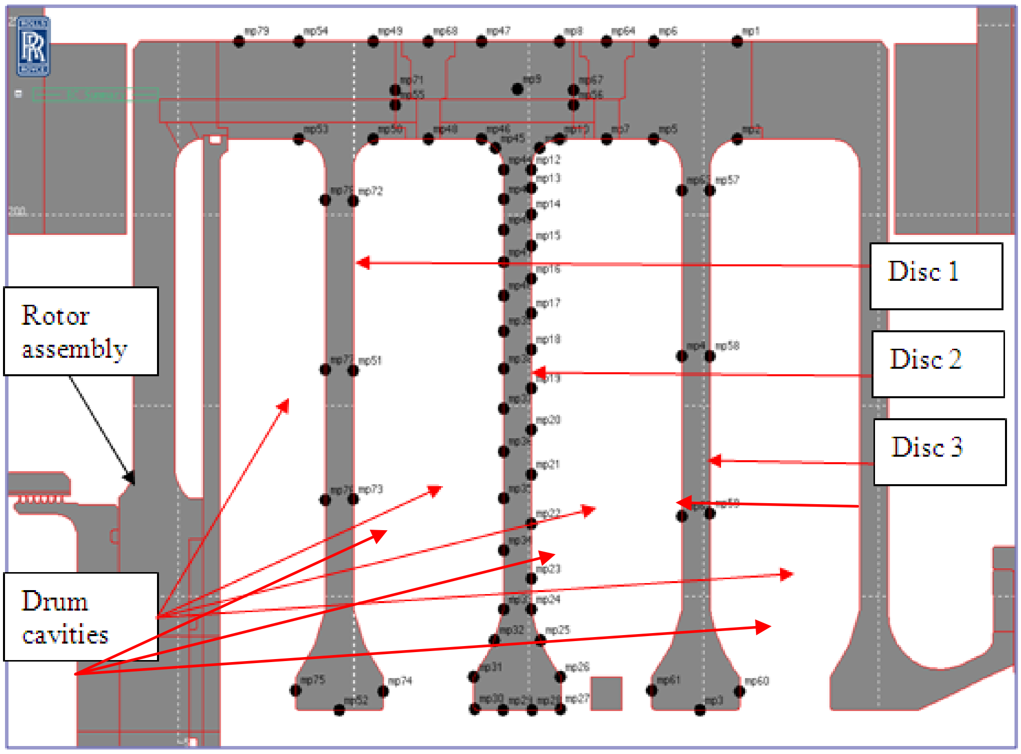


Figure 1.1: Rotor of the multiple cavity rig with instrumentation points

The rig was designed to be not only representative of typical current engine geometry, but also able to run as close as possible to typical non-dimensional operating conditions.The SC03 model of the Rotor of the multiple cavity rig with instrumentation points, discs and drum cavity is presented as Figure 1.1. For a detailed description of the multiple cavity rig the reader is referred to Alexiou (2000), Long and Childs (2007), Long, Miché and Childs (2007) and Miché (2008). In this investigation, a mathematical method known as the Lumped modelwas used for the study as such the parametric predicted results from the SC03 model of the MCR are compared with a mathematical model results in this paper.

II. METHODOLOGY

The methodology employed include the Grid Independence study, model analysis using SC03 and the thermal matching. This thermal matching involves the calibration of the finite element thermo-mechanical model against the mathematical model. This validation of the SC03 model data against the lumped parameter result,are presentedsection 4.The SC03 model analysis is performed with the understanding that it is similar to a simplified model such as a single rotating cavity with two discs separated from each other by a shroud of axial gap sand the outside radius of the discs is *b*, while the inside radius of the discs, or bore, is *a*. According to Owen and Rogers (1995), Chew (1982), Pincombe (1983), Long (1984) and Farthing (1988) and all symbols retaining their usual nomenclatures, the gap ratio of the cavity *G* is defined as:

$$G = \frac{s}{b} \qquad \textbf{(2.1)}$$

The rotational speed of the cavity is Ω and the bulk average velocity of the axial throughflow is W.

$$W = \frac{\dot{m}}{\rho A_{an}} \qquad \textbf{(2.2)}$$

For a fluid of kinematic viscosity v,the rotational Reynolds number is defined as:

$$\mathrm{Re}_{\phi} = \frac{\Omega b^{2}}{\nu} \qquad \textbf{(2.3)}$$

The axial Reynolds numbers which isthe parameter that characterises the axial throughflow of airis defined as:

$$\mathrm{Re}_{z} = \frac{W d_{h}}{\nu} \qquad \textbf{(2.4)}$$

*Corresponding Author: Ekong, Godwin I.

where d_h is the hydraulic diameter of the inlet. In case of a cavity without an inner shaft, $d_h = 2a$, while for one with an inner shaft of radius, r_s, $d_h = 2(a - r_s)$.

The Rossby number, Ro is defined which is the ratio of the mean velocity of the throughflow to the tangential velocity of the disc at the bore radius is given as:

$$Ro = \frac{W}{\Omega a} \tag{2.5}$$

The Rossby number Ro links the effect of both rotation and the inertia of the throughflow and can also be expressed in terms of the rotational and axial Reynolds numbers as:

$$Ro = \frac{b^2 \operatorname{Re}_z}{2a(a - r_s)\operatorname{Re}_\phi} \tag{2.6}$$

The Grashof number Gr which is a non-dimensional quantity in fluid dynamics and heat transfer, approximates the ratio of the buoyancy to viscous force acting on a fluid and is expressed as:

$$Gr = \frac{\Omega^2 b \beta \Delta T L^3}{\nu^2} \tag{2.7}$$

In a rotating cavity application according to Farthing et al. (1992b), Grashof numberis based on the radial distance along the disc surface is based on the local surface temperature and its relative centripetal acceleration by taking y as a height reference from the shroud. For a vertical plate, the flow transitions to turbulent around a Grashof number of 10^9.

The Prandtl number Pr is which is a dimensionless property of a fluid, is the ratio of the kinematic viscosity to the thermal diffusivity at a given point and is given as:

$$\Pr = \frac{\nu}{\alpha} \tag{2.8}$$

For a comprehensive analysis of flow in rotating cavities and various flow configuration, the reader is referred to works bywork by Dorfman (1963), Chew (1982), Pincombe (1983), Long (1984), Farthing (1988), Owen and Rogers (1989), Tucker (1993), Owen and Rogers (1995) and Childs (2011).

2.2 Grid Independence study

In SCO3 finite element program, the mesh is generated automatically when the analysis is run. The SC03 program has an inbuilt automatic mesh generator made up of quadratic, six-node triangular elements.

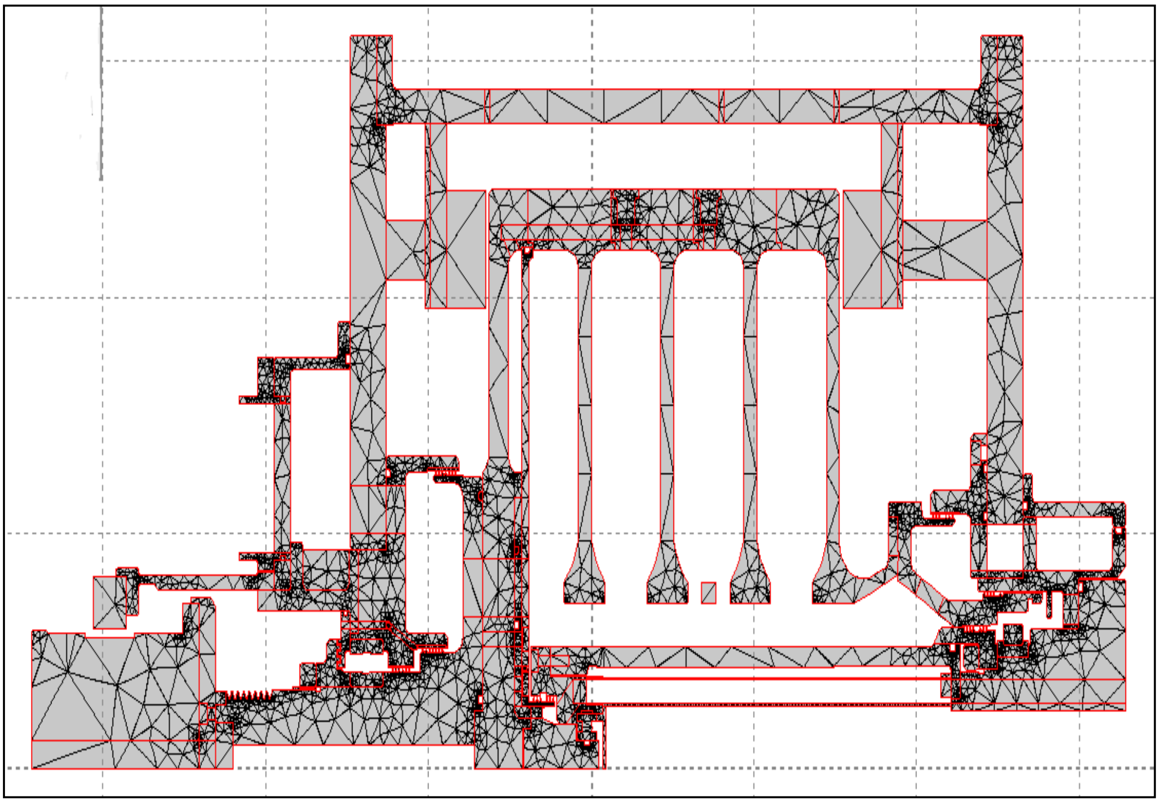


Figure 2.1: The geometry of the multiple cavity rig model meshed with six-node triangular elements in 2D

The element density is controlled by the triangle distortion ratio, with a default value of 4. The thermal accuracy employed in this study for both steady state and transient cycles, was set to 2°CA converged solution was produced after four (4) refinements as presented in Table 2.1 and the grid independent result for the third and fourth refinements are presented graphically by plotting the transient temperature result for model point MP7 as shown in Figure 2.2.

Table 2.1: The third (3rd) and fourth (4th) refinementmeshes properties (Ekong 2014)

SN	Properties	Third (3rd) refinement	Fourth (4th) refinement
1	Time (s)	0.631572	0.690967
2	Elements	9942	10007
3	Nodes	22475	22504

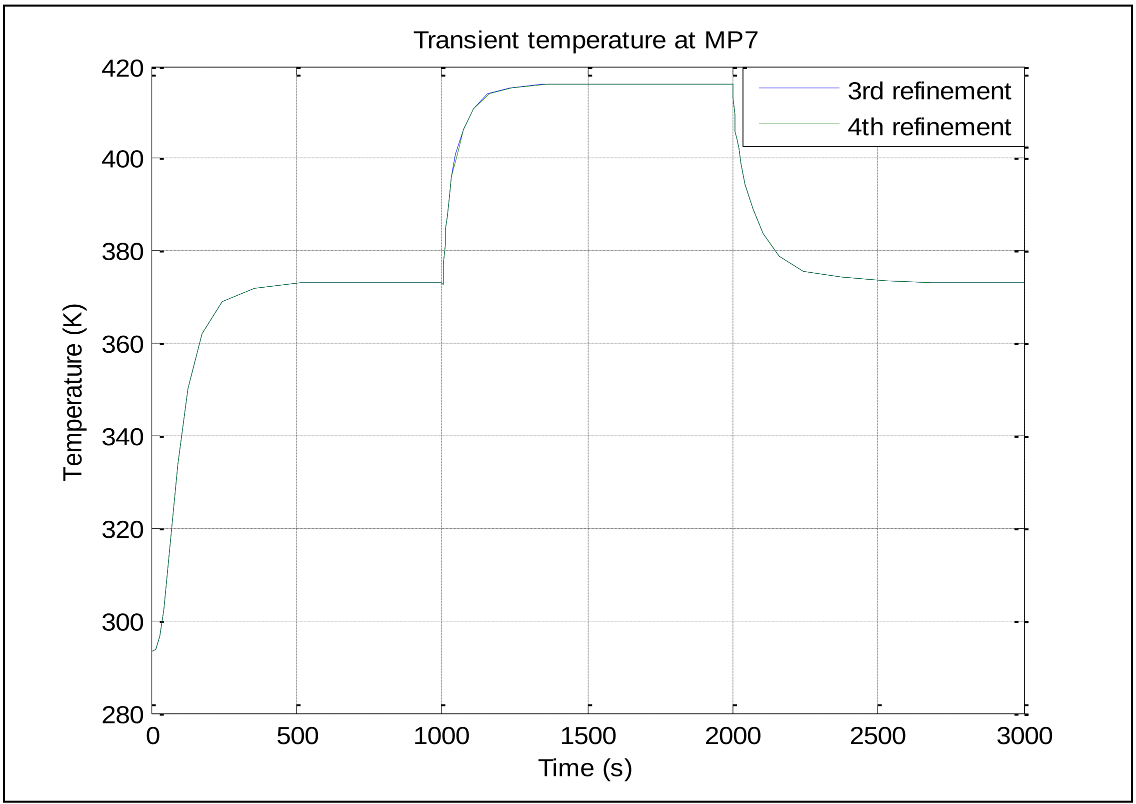


Figure 2.2: A transient plots of the third (3^{rd}) and fourth (4^{th}) refinement meshes solutions for model point MP7

Figure 2.1 shows a transient plot of the third (3^{rd}) and fourth (4^{th}) refinement mesh solutions for model point MP7. This indicates that there no change in the results of metal temperature at MP7 for both meshes during engine transient, hence the results were independent of the grid.

2.2 Validation Process

This is the matching exercise, whereby, the finite element thermo-mechanical model is calibrated against the engine measurements or a mathematical model. The requirements for the matching exercise in this study include the thermo-mechanical model of the MCR with disc 2 upstream predicted data from the square cycle and the mathematical parameter model results of the cycle. The SC03 model produced provide transient thermal simulations which are run with user-defined operating cycle is shown as Figure 2.3.In this finite element program, the internal temperature distribution of the rig components using the transient is computed. The heat conduction equation with appropriate thermal boundary conditions are also employed in the model to account for the convective and radiative heat transfers. The convective boundary conditions are accounted for in the model by specifying flow distribution, local air temperatures, and heat transfer coefficients based on Nusselt number correlations (Ekong 2014). To calibrate the finite element thermal model against a mathematical model parameter data, the mathematical parameter data are presented graphically and compared with the model results. However, the required temperature accuracy during thermal matching, according to Rolls Royce standardis ± 5K for transient and ± 2K for steady state (Rolls-Royce, 2004).

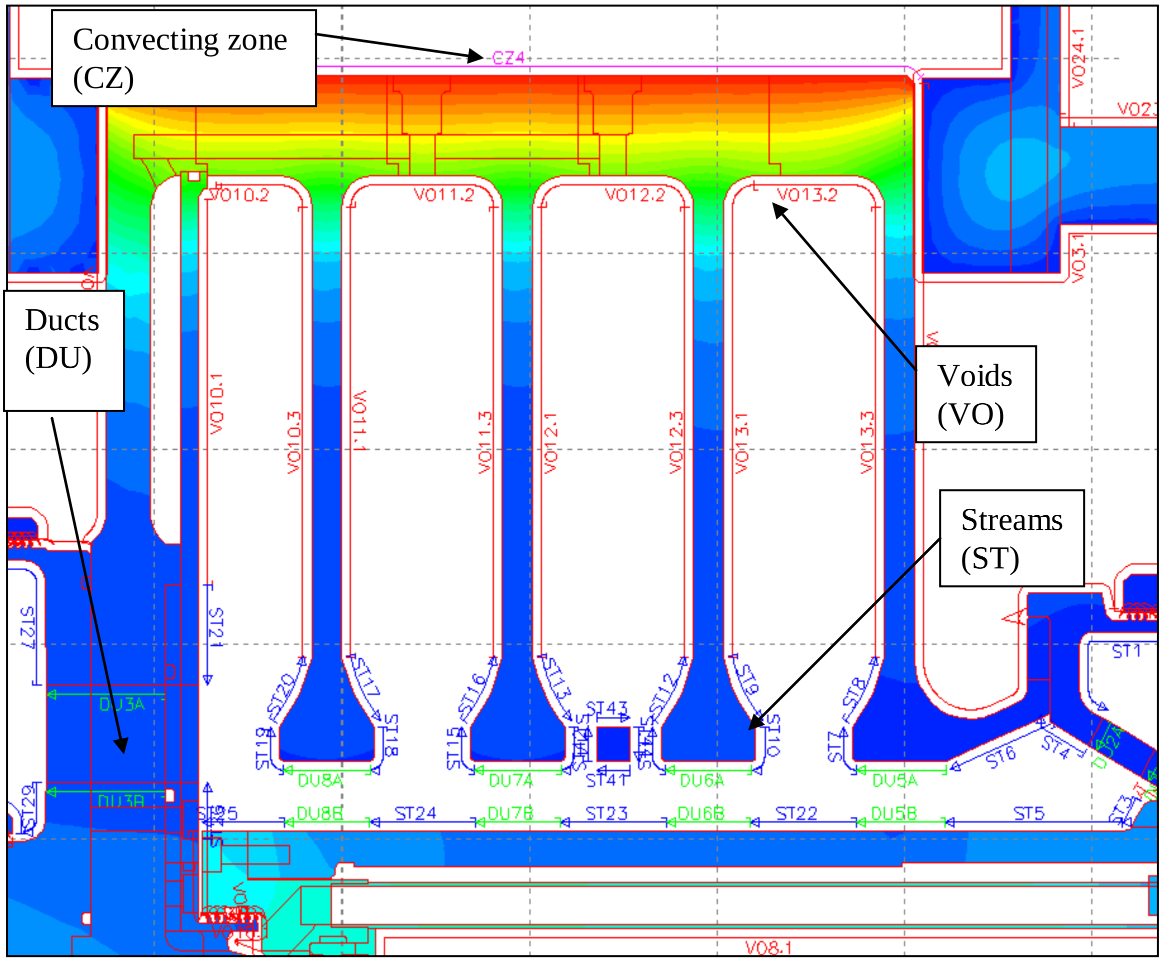


Figure 2.3: SC03 model of the Multiple Cavity Rig (MCR) with boundary conditions

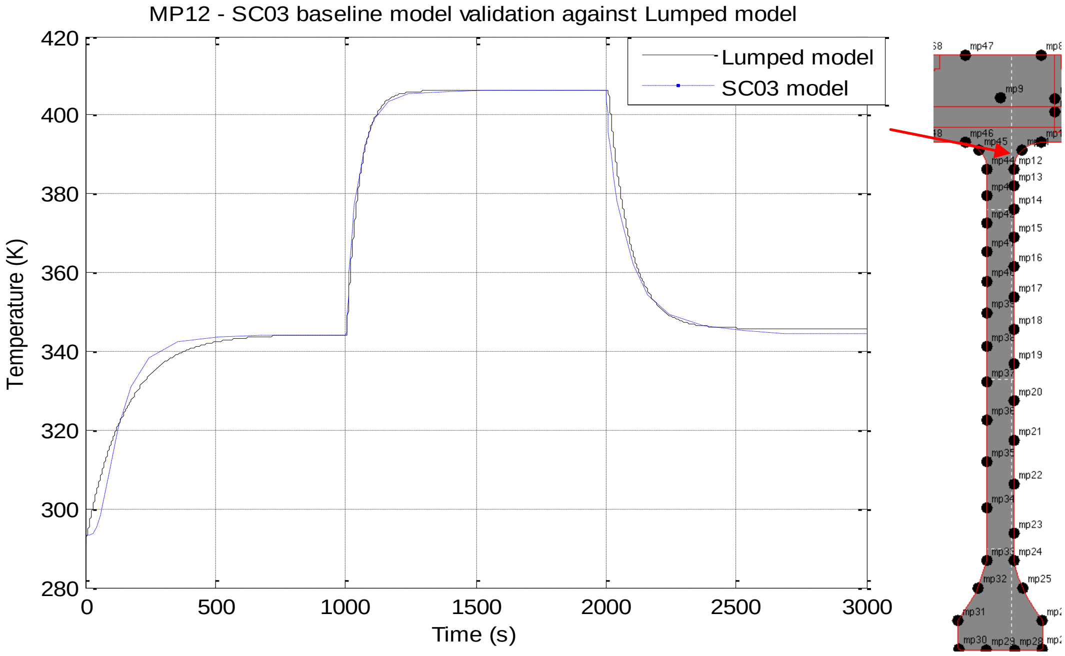
III. RESULTS AND DISCUSSION

3.1 Validation of SC03 data against the Mathematical Parameter Model

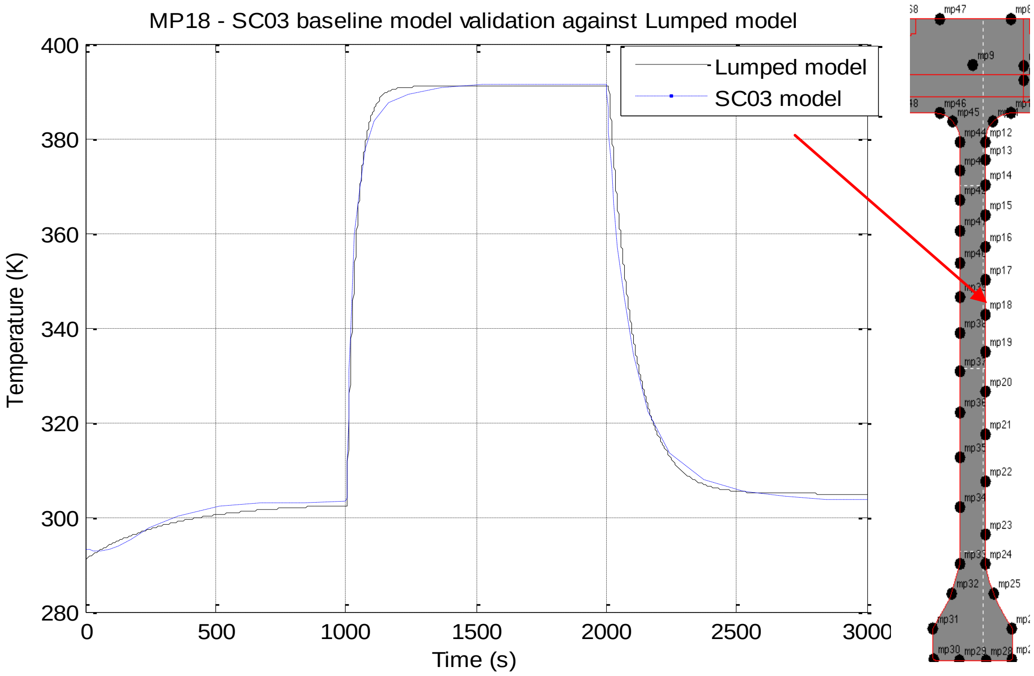
In this section, the finite element thermo-mechanical models are calibrated against the mathematical parameter models. The predicted temperature profiles of both SC03 baseline and 6% radial inflow models are matched with those of the lumped model data to show the similarity of the profiles within an acceptable accuracy. In this study, the validations are performed at model points MP12, MP18and MP28 on disc 2 upstream in cavity 3. Section 3.2 describes the validation of the baseline models (model without radial inflow) while the validation of the models with radial inflow is presented in section 3.3.

3.2 Validation of baseline models

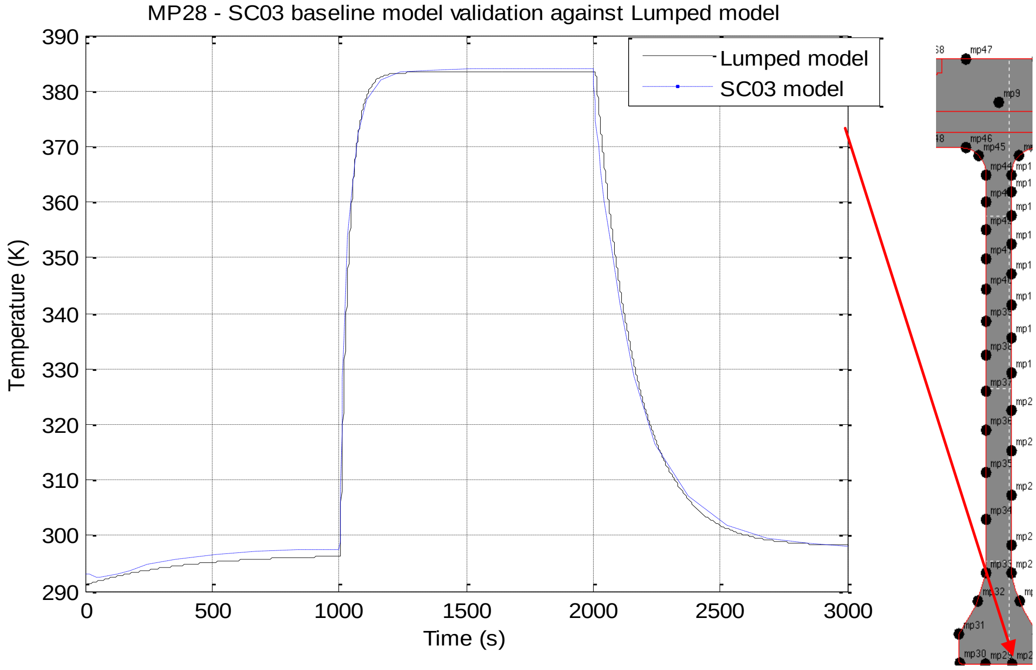
This section presents, the validation of the SC03 baseline model against the lumped model for model point MP12, MP18 and MP28 respectively. The baseline model is the model without radial inflow.Figures 3.1 through to 3.3 illustrate the validation process involving the SC03 baseline model against mathematical parameter model called the Lumped model at model points MP12, MP18and MP28respectively. This matching process indicates that the predicted temperature for stabilised Idle,stabilised max-take-off (MTO), the time constant during acceleration and deceleration at MP12, MP18 and MP28respectively match the lumped model results.



Figures 3.1: The validation of SC03 models against the lumped model for the baseline model at model points MP12



Figures 3.2: The validation of SC03 models against the lumped model for the baseline model at model points MP18

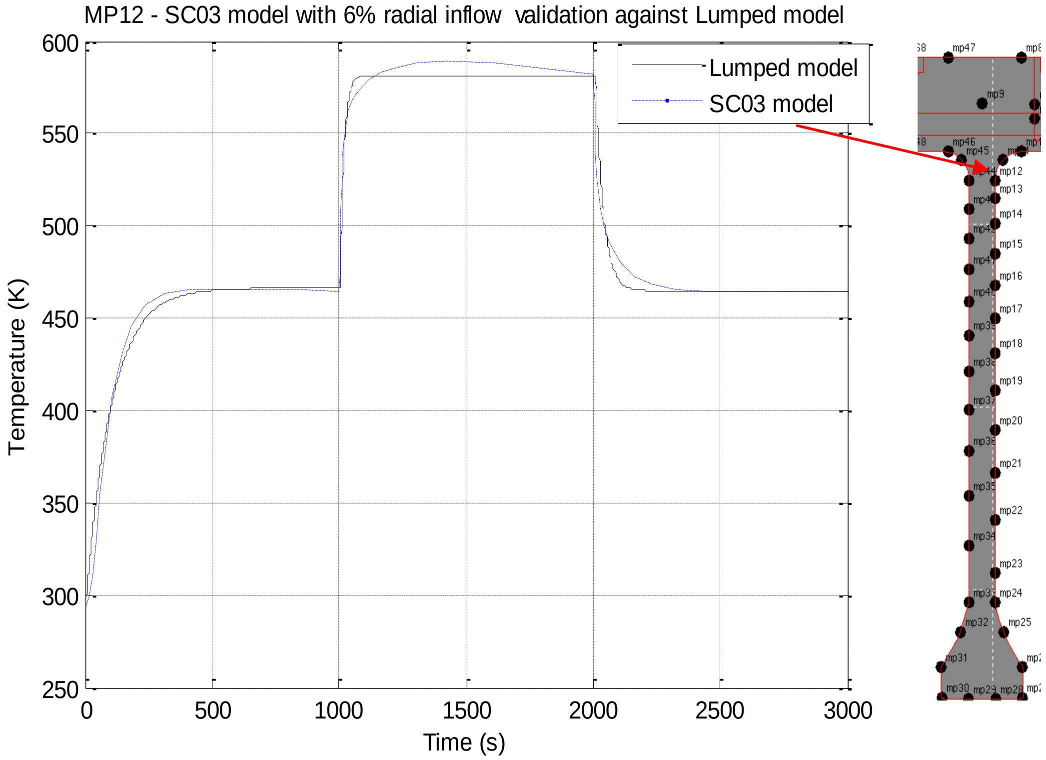


Figures 3.3: The validation of SC03 models against the lumped model for the baseline model at model points MP28

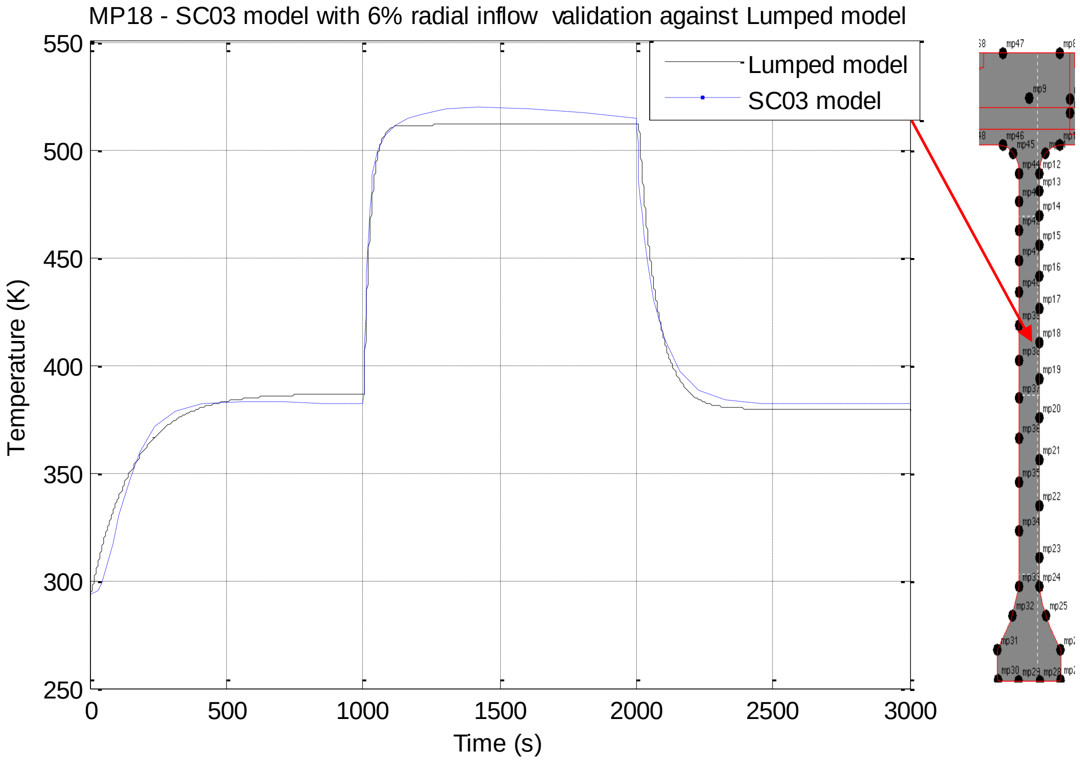
3.3 Validation of models with radial inflow

This section presents, the validation of the SC03 model with 6% radial inflow against the lumped mathematical model for model point MP12, MP18 and MP28. Figures 3.4 through to 3.6 illustrate the validation process at model points MP12, MP18and MP28respectively. This matching process indicates that the predicted temperature for stabilised Idle,stabilised max-take-off (MTO), the time constant during acceleration and deceleration at MP12, MP18 and MP28respectively match the lumped model results. The SC03 model slightly over-predicted temperature at max take off region (MTO) at model points MP12 and MP18 but were within the acceptable accuracy. However, the validation for model point MP28 was in good agreement with the lumped model throughout the transient.

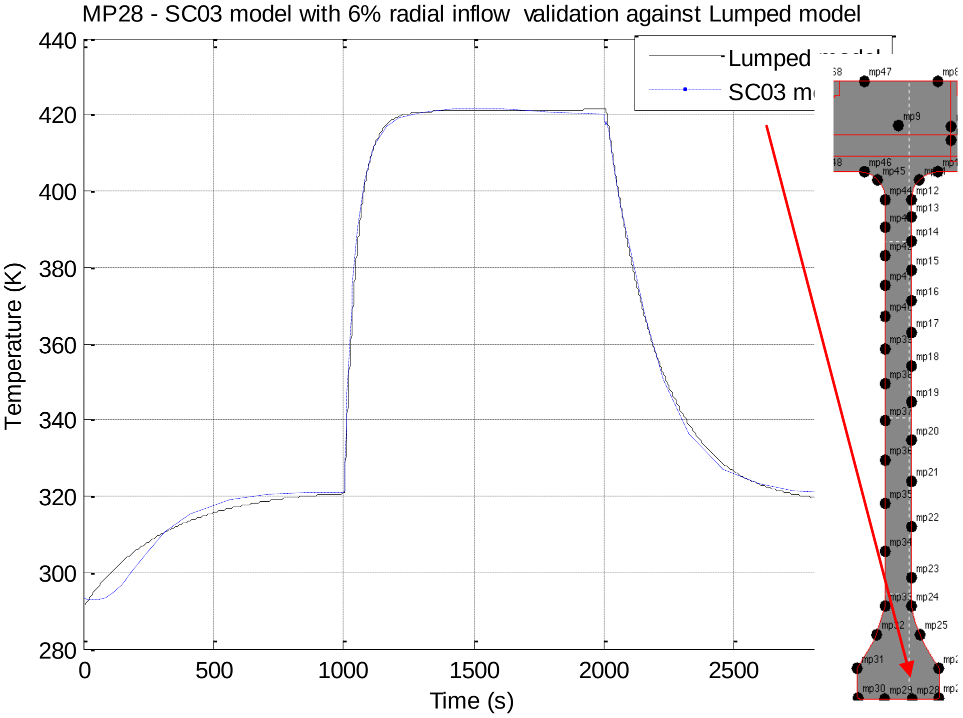
.



Figures 3.4: The validation of SC03 model with 6% radial inflow against the lumped model at model points MP12



Figures 3.5: The validation of SC03 model with 6% radial inflow against the lumped model at model points MP18



Figures 3.6: The validation of SC03 model with 6% radial inflow against the lumped model at model points MP28

In summary, the comparison shows good agreement between the lumped parameter model and the SC03 predicted results for both models with 6% radial inflow and the baseline model at model points MP12, MP18 and MP28.

IV. CONCLUSION

The heat transfers and fluid flow in the multiple cavity model highlighted the nature of flow inside the cavities similar to those found in the high pressure compressor in real engine. Hence, the need for the modelling, taking into consideration the relevant heat transfer coefficient correlations used in the boundary conditions in the multiple cavity rig model. The modelling of the multiple cavity was performed using a finite element analysis program known as SC03, a Royce-Roll in-house finite element analysis program. This paper presented the validation of the SC03 model data against the mathematical model results(lumped parameter model).The predicted temperature profiles and time constant data of both SC03 baseline models and 6% radial inflow models were matched with those of the lumped model data to show the similarity of the profiles within an acceptable accuracy. The validations were performed at model points MP12, MP18 and MP28 on disc 2 upstream in cavity 3. The overall result of the matching process shows that the results of the lumped model are in good agreement with the results of the two MCR models (baseline model and model with 6% radial inflow). Evidence in the matching profiles of the two models, hence, the validation is achieved since the predictions from the SC03 models are in good agreement with the mathematical model results.Hence, this mathematical model is good and can be used independently for the prediction and determination of the effect of the various parameters on tip clearance in high pressure compressor during engine transient.

ACKNOWLEDGMENTS

I acknowledged my supervisors during my research years at Thermo-Fluid Mechanics Research Centre, University of Sussex, Brighton, BN1 9QT, United Kingdom Prof. Peter R. N. Childs, Dr. Christopher A. Long and Dr. Nick. R. Atkins 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]. Monico, R. D and Chew, J. W (1993) Modelling thermal behaviour of turbomachinery discs and casings. Proceedings of Agard Conference 527 held in Antalya, Turkey12th -16th October 1992 ISBN 92-835-0701-0 Published Febraury 1993.

[2]. Alexiou, A. (2000) Flow and heat transfer in gas turbine H.P. compressor internal air systems. D.Phil. thesis, School of Science and Technology, University of Sussex.

[3]. Long, C. A. & Childs, P. R. N (2007) Shroud heat transfer measurements inside a heated multiple rotating cavity with an axial throughflow of air. International Journal of Heat and Fluid Flow**,**Volume 28, Issue 6, Pages 1405–1417.

[4]. Long, C. A., Miché, N.D.D., Childs, P.R.N. (2007) Flow measurements inside a heated multiple rotating cavity with axial throughflow. International Journal of Heat and Fluid Flow**,**Volume 28, Issue 6, Pages 1391–1404.

[5]. Mich´e, N. D. D. (2008) Flow and heat transfer measurements inside a heated multiple rotating cavity with axial throughflow. PhD thesis, University of Sussex.

[6]. Dorfman, L. A. (1963) Hydrodynamic resistance and the heat loss of rotating solids. Edinburgh, Oliver and Boyd.

[7]. Chew, J. W. (1982). Computation of flow and heat transfer in rotating cavities. D.Phil. Thesis, School of Engineering, University of Sussex, UK.

[8]. Long, C. A. (1984) Transient heat transfer in a rotating cylindrical cavity. D.Phil. thesis, School of Engineering, University of Sussex, UK.

[9]. Farthing, P. R. (1988) The effect of geometry on flow and heat transfer in a rotatingcavity. D.Phil. thesis, School of Engineering, University of Sussex, UK.

[10]. Owen, J. M. & Rogers, R. H. (1989) Flow and heat transfer in rotating-disc systems: Vol. 1, rotor-stator systems. Taunton, UK & Wiley, NY, Research Studies Press.

[11]. Owen, J. M. & Rogers, R. H. (1995) Flow and heat transfer in rotating-disc systems: Vol. 2, rotating cavities. Taunton, UK & Wiley, NY, Research Studies Press.

[12]. Childs, P. R. N. (2011) Rotating Flow. Elsevier Inc. ISBN 978-0-12-382098-3.

[13]. Pincombe, J. R. (1983) Optical measurements of the flow inside a rotating cylinder.

[14]. D.Phil. thesis, School of Engineering, University of Sussex, UK.

[15]. Tucker, P. G. (1993) Numerical and experimental investigation of flow structure and heat transfer in a rotating cavity with an axial throughflow of cooling air. D.Phil. thesis, School of Engineering, University of Sussex, UK.

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

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