Modeling and Analysis of Dry Low Emission Combustor Discharge Nozzle Material & Structure for Rolls Royce Industrial RB211 Gas Turbine

by

Amalina Binti Daud

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

MAY 2011

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Modeling and Analysis of Dry Low Emission Combustor Discharge Nozzle Material & Structure for Rolls Royce Industrial RB211 Gas Turbine

by

Amalina Binti Daud

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING(Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Mohd. Faizairi Mohd. Nor)

Mohd Faizairi Mohd Nor
Lecturer
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
31750 Tronoh
Perak Darul Ridzuan, Malaysia

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AMALINA BINTI DAUD

ABSTRACT

The title of this dissertation is Modeling and Analysis of Dry Low Emission Combustor Discharge Nozzle Material and Structure for Rolls Royce Industrial RB211 Gas Turbine. Rolls Royce is looking into possible or alternative material for the discharge nozzle in DLE Combustor in order to increase the cycle usage or service life based on stress, deformation and heat flux to reduce their maintenance cost. Service life or cycle usage of the discharge nozzle is basically reduced by high stress, deformation, and total heat flux. The possible improvement in terms of the alternative material and the right geometrical structure will help to solve this problem. The objectives are to model and analyze the discharge nozzle in DLE Combustor in Industrial Rolls Royce RB211 Gas Turbine, to do Finite Element Analysis (FEA) modeling and to analyze stress, total heat flux, and total deformation in the discharge nozzle structure by changing the geometry and material and lastly to find alternative material for the discharge nozzle. The project uses two different software for designing and simulation which are AUTODESK INVENTOR Professional 2010 and ANSYS software. The scope of study are modeling and analysis of Dry Low Emission Combustor Discharge Nozzle Structure for Rolls Royce RB211 Gas Turbine, FEA modeling and analyzing stresses, total heat flux, and deformation in the discharge nozzle structure for Rolls Royce RB211 Gas Turbine by changing the geometry and material, possible improvement in terms of material for the discharge nozzle by focusing on the service life and lastly alternative material for the discharge nozzle of RB211 Gas Turbine. The methodology consists of flow of the project and the method of using AUTODESK INVENTOR Professional 2010 and ANSYS software. Three different geometry and materials are compared. The geometrical changes are based on the three different exhaust areas resulted by three different height setting. The actual exhaust area is 0.0225 m^2 (Model C). The impact is analyzed by changing the area to 0.018 m^2 (Model A) and 0.02025 m^2 (Model B). It is found that Model B is appropriate to satisfy low deformation and low stresses requirement. Three materials are chosen which are Hastelloy X, Haynes 230 and Haynes 214. From the findings, Haynes 230 will be the best alternative material for the discharge nozzle because it has the lowest Von Mises Stress, Intensity of Stress and total heat flux.

ACKNOWLEDGEMENT

I would like to take this opportunity to acknowledge and thank everyone that has given me all the supports and guidance throughout the whole period of completing the final year project. First of all, I must also acknowledge the endless help and support received from my supervisor, Mr. Mohd Faizairi Mohd Nor throughout the whole period of completion of the final year project. His supervision and opinion are very much appreciated. Apart from that, I also would like to thank OTEC Kemajuan Sdn. Bhd. and Rolls Royce to gives me an opportunity to familiarize with Rolls Royce RB211 Dry Low Emission system and undergo the training on Dry Low Emission combustor of Rolls Royce RB211 during my industrial training in United Kingdom. Their continuous support and help are very much appreciated. Finally, thanks to my colleagues for their aid and advice. Thank you.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHS

ABBREVIATION

IP	Intermediate Pressure
HP	High Pressure
FEA	Finite Element Analysis
DLE	Dry Low Emissions

CHAPTER 1
INTRODUCTION

1.1 Background of project

This project focuses on Modeling and Analysis of Dry Low Emission Combustor Discharge Nozzle Structure for Rolls Royce RB211 Gas Turbine. Dry Low Emission (DLE) combustion system is a new technology used in gas turbine introduced to reduce pollution by stabilizing the emission of greenhouse gasses in atmosphere. This project focuses more on modeling and analyzing stresses, total heat flux and deformation in the discharge nozzle structure of Dry Low Emission (DLE) combustor for Rolls Royce RB211 Gas Turbine by changing the geometry and material using Autodesk Inventor 2010 and ANSYS 11.0. Rolls Royce requires a possible improvement in terms of material used for the discharge nozzle by focusing more on the cycle usage or service life and combustion environment sustainability. This project is very important for Rolls Royce in order to decide the alternative material for the discharge nozzle of RB211 Gas Turbine Dry Low Emission (DLE) combustor.

1.2 Problem Statement

Rolls Royce is looking into possible/alternative material for the discharge nozzle in DLE Combustor in order to increase the cycle usage/service life based on stress, deformation and heat flux to reduce their maintenance cost. Service life or cycle usage of the discharge nozzle is basically reduced by high stress, deformation, and total heat flux. The possible improvement in terms of the alternative material and the right geometrical structure will help to solve this problem.

1.3 Objective and Scope of Study

1.3.1 The objectives of this project

- To model and analyze the discharge nozzle in DLE Combustor in Industrial Rolls Royce RB211 Gas Turbine
- To do FEA modeling and analyze stress, total heat flux, and total deformation in the discharge nozzle structure by changing the geometry and material
- To find alternative material for the discharge nozzle

1.3.2 Scope of Study

This project covers three main scopes which are

- Modeling and Analysis of Dry Low Emission Combustor Discharge Nozzle Structure for Rolls Royce RB211 Gas Turbine.
- FEA modeling and analyzing stresses, total heat flux and deformation in the discharge nozzle structure for Rolls Royce RB211 Gas Turbine by changing the geometry and material.
- Possible improvement in terms of material for the discharge nozzle – focusing on the service life and sustainability.
- Alternative material for the discharge nozzle of RB211 Gas Turbine.

CHAPTER 2
LITERATURE REVIEW

2.1 Rolls Royce RB211 Dry Low Emission Combustion system

Combustor technology in gas turbine has been developed gradually and continuously. New concept and technology are needed to further reduce pollutant emissions and respond to the growing requirement of multi fuel capability. The simplest form of combustor made is a straight walled duct connecting the compressor to the turbine which is called conventional combustion system. This early designed of combustor impractical because of excessive pressure loss. The combustor of gas turbine must satisfy wide range of requirements such as

- ❑ High combustion efficiency which require complete combustion
- ❑ Reliable and smooth ignition
- ❑ Wide stability limit
- ❑ Low pressure loss
- ❑ Compatible size and shape
- ❑ Maintainability
- ❑ Minimum cost and ease of manufacturing
- ❑ Durability and Multi-fuel and capability

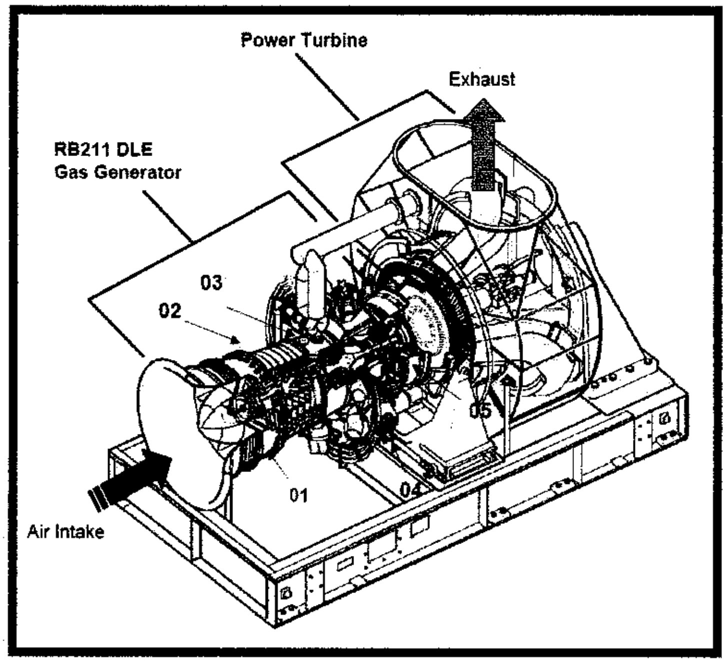


Figure 1: Industrial Rolls Royce RB211 DLE
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

The figure shows Industrial RB211 DLE gas generator. It is a gas fired, aero derived gas turbine, incorporating a Dry Low Emissions (DLE) combustion technique which is used to achieve simultaneous control of NOx and CO emissions. The gas generator of Rolls Royce RB211-DLE features two spools designed for high pressure ratio operation. The first Intermediate Pressure (IP) spool consists of seven-stage axial compressor coupled to a single-stage turbine. Concentric with this is the High Pressure (HP) spool consist of six-stage compressor and single-stage turbine.

The combustion system features nine individual radially-mounted combustion chambers incorporating a multiple series stage, premix lean burn combustion technique, between the compressor and turbine sections. The two spools are mechanically independent, allowing each to run at its optimum speed.

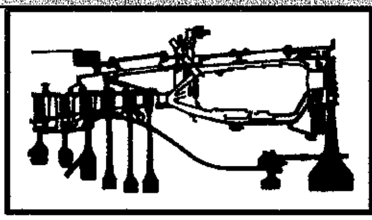
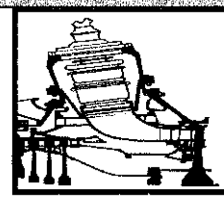
The technique of premix lean burn enables the combustion temperature to be controlled within the necessary limits but requires the fuel staging to provide turndown without encountering flameout. Series fuel staging provides the widest combustion stability margins and hence the widest operating range. To achieve acceleration to idle and low power operation a conventional diffusion flame system is incorporated into the fuel injector. In addition, a torch ignitor system is provided to ensure reliable starting. Therefore a two-stage combustor has four separate fuel feeds to:

- ❑ Torch: for ignition only
- ❑ Central Diffusion: for low power operation
- ❑ Primary Premix: for low emissions
- ❑ Secondary Premix: for operation

To achieve the required combustion parameters the Dry Low Emission combustion system arrangement consists of nine radially-mounted tubular combustors. The control of the combustion process for start-up and transfer from central diffusion to premix lean burn operation is accomplished by the integrated Engine Management System (EMS). This ensures that the correct air fuel ratio is achieved under the varying operating conditions to minimize emissions. Standard features of Rolls Royce RB211 Dry Low Emission Combustors are:

- ❑ Series Staged Combustion with two stage of combustion
- ❑ 9 Combustors that have no inter-connectors
- ❑ Twin Ignitors Per Combustor
- ❑ Torch Ignition for Starting
- ❑ Central Diffusion takes engine to 50% power
- ❑ Primary Pre Mix and Secondary Pre Mix. Pre Mix takes Engine to 100% power

Table 1: Comparative diagrams of conventional and DLE Combustor system (Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

Standard Conventional	**Dry Low Emissions (DLE)**
	
Single annular combustor with 18 off conventional fuel injectors which is smaller in size compared with DLE Combustor	9 off pre mix lean burn combustors (9 combustors with 80% increase in volume compared to standard combustor which is fitted radially to accommodate volume increase within the same length)

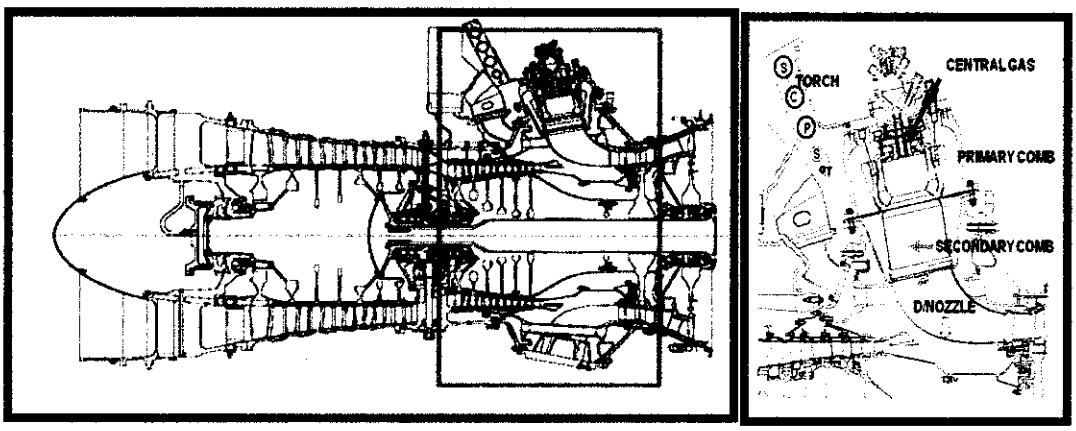


Figure 2: DLE Combustor Location and components in Rolls Royce RB211 Gas Turbine (Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

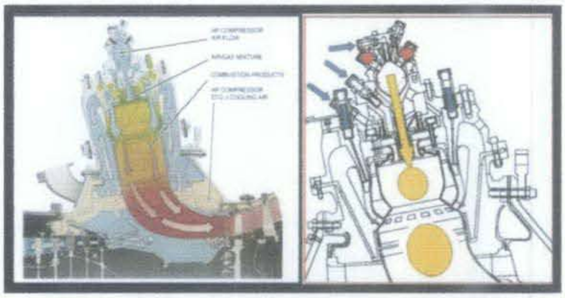


Figure 3: Combustion system of Dry Low Emissions in Rolls Royce RB211
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

2.1.1 The Concept of Dry Low Emission Combustors

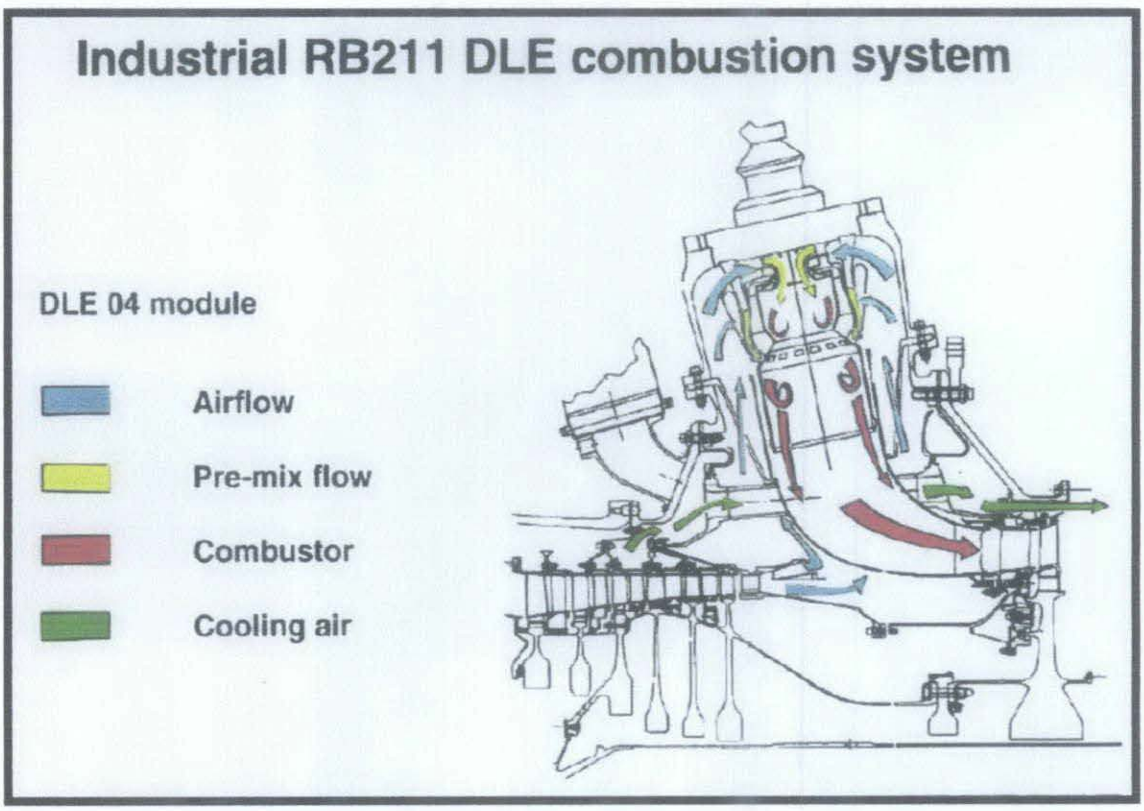


Figure 4: Industrial RB211 DLE Combustion System
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

The combustion section consists of nine exterior radially mounted combustors. Each of combustors has a torch, central, primary, and secondary flow fuel injection. **Torch ignition** used to achieve acceleration to premix lean burn operation. Fuel premixed with air from compressor which is guide by an angled High Pressure Nozzle Guide Vane to combustors and added in stages which is primary and secondary to achieved controlled low emission combustion. The torch provides ignition to the central diffusion injector. The torch itself is ignited by electrical discharge igniter plugs located in the discharge igniter head. The torch assembly consists of torch liner assembly, torch swirler and torch gas injector. Two igniters located at the head of each combustor to provide the electrical ignition to the torch burners.

The primary zone is fed by two counter rotating air-swirlers, with several gaseous fuel injection points located at passageway. **The secondary mixing duct** is wrapped around the primary combustor but is separated from it by another annular duct which provides the wall cooling air. Gaseous fuel is injected into secondary duct from 36 equivalent spaced axial spray bars, each containing six injection holes. Fuel Sampling and Combustion test showed uniformity of fuel air mixing to within 4%. The figure below shows the schematic diagram of RB211 Combustor.

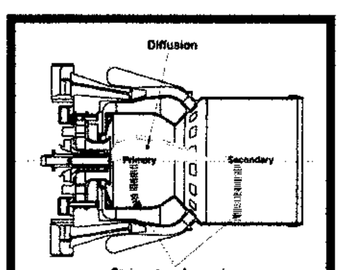


Figure 5: Schematic Diagram of RB211 Combustor

(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

Combustion testing carried out over a range of pressures from **0.1** to **2.0 MPa** demonstrated the ability of this axially staged DLE to achieve simultaneously low NOx and CO over wide range of power and ambient. Air flows from high pressure compressor to combustors and mix with gaseous fuel. High pressure compressor air also used to cool down the combustion temperature to certain level.

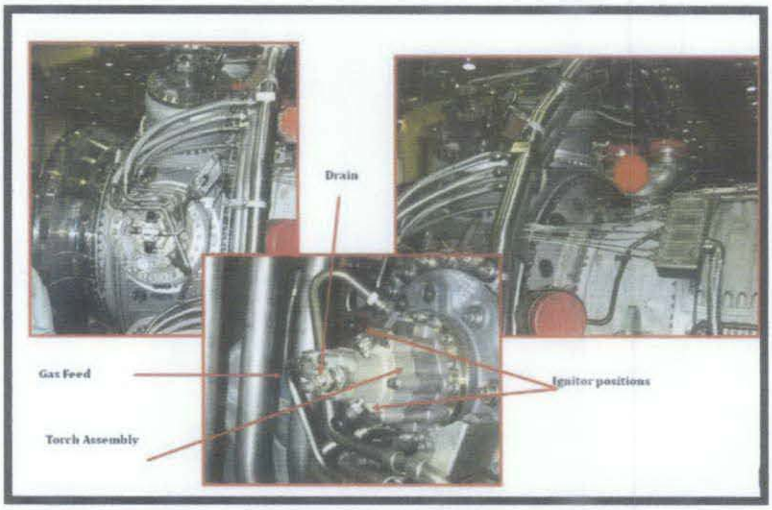


Figure 6: Torch Assembly, Ignitor positions, Drain and Gas Feed
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

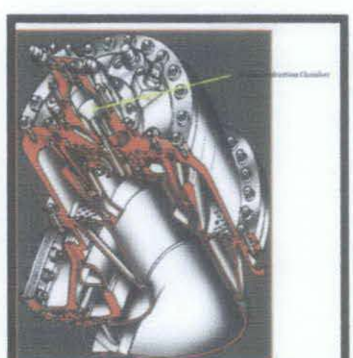


Figure 7: Torch of Combustion Chamber
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

Figure 8: HP Nozzle Guide Vane

(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

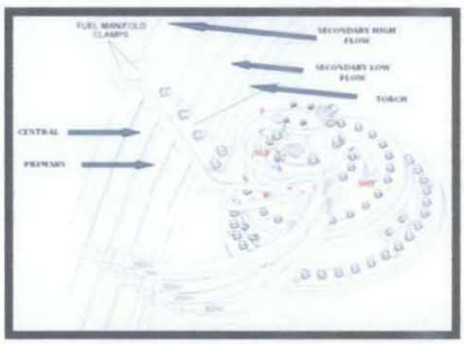


Figure 9: Five manifolds arranged circumferentially around gas generator and secured by mounting plates which are torch, secondary low flow, primary, central, and secondary low flow

(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

Figure 10: Liner and Splitter

(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

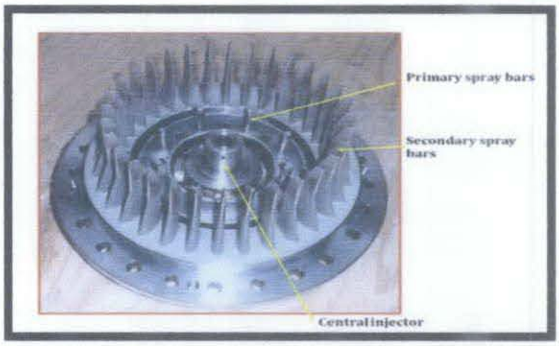


Figure 11: Primary Spray Bars, Secondary Spray Bars and Central Injector
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

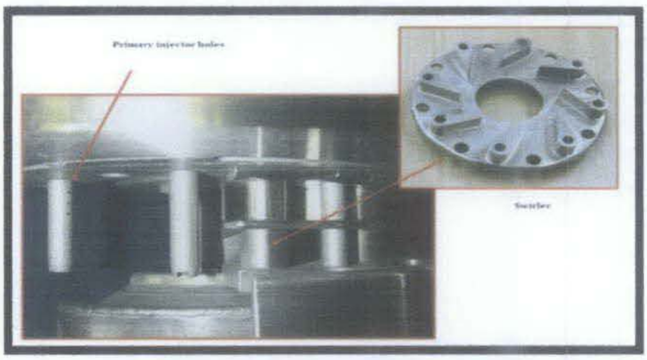


Figure 12: Primary Injection Holes and Swirler
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

Figure 13: Secondary Gas Feed and Injector Holes
(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

2.1.2 Technical Data of RB211-24 G DLE

<u>DIMENSIONS</u>

Length:	2.9m
Maximum Diameter:	2.18m

<u>WEIGHT</u>

Basic Dry Weight:	3100 Kg
Gas Generator Plus Stand:	4000 Kg

<u>COMPRESSOR</u>

Type:	Axial Twin Spool (Built up rotor)
No of stages:	IP 7 and HP 6
Split line:	Horizontal/Vertical
Normal Operating Speed:	6643 RPM (IP) and 9445 RPM (HP)
Maximum Tip Speed:	355 m/s
Maximum Continuous Speed:	6720 RPM (IP) and 9550 RPM (HP)

<u>TURBINE</u>

No of stages:	2
Split line:	Vertical
Normal Operating Speed:	6643 RPM (IP) or 9445 RPM (HP)
Maximum Tip Speed:	525 m/s
Maximum Continuous Speed:	6720 RPM (IP) and 9550 RPM (HP)

COMBUSTOR

Type:	Radially mounted premix lean burn series staged combustion chambers
No of burners:	9
No of Injectors:	One set per combustion chamber
No. of Igniters:	2 per combustion chamber

BEARINGS:

Radial Type:	Roller (squeeze film)
Thrust Type:	Double Ball
Number per Shaft:	IP 3 and HP 2

OTHERS:

Idle Speed:	3250 RPM (IP)
Maximum Operating Temperature(EGT):	780 ^{o}C
Critical Speeds:	Outside Operating Range
Maximum Vibration:	25 mm/s average velocity
Normal Vibration:	Less than 21 mm/s average velocity
Normal Vibration Alarm:	3.5 mm/s average velocity above initial normal running levels
Lube Oil Pressure Maximum Supply:	7.6 to 8.3 bar at 350 igph, 60 ^{0}C
Oil Consumption:	Average : Less than 0.19 Liters/Hour

PERFORMANCE IN ISO CONDITIONS WITH NO LOSSES IN GASEOUS FUEL

Output shaft:	39500hp
Heat Rate:	9473 KJ/kWh or 6695 Btu/hph
Exhaust Mass Flow:	94.3 kg/s or 208 lb/s
Exhaust Temperature:	490^{0}C or 914^{0}F
Thermal Efficiency:	Up to 40.5%

2.2 Dry Low Emission Combustor Discharge Nozzle in Rolls Royce Gas Turbine

The design of discharge nozzle in Dry Low Emission combustor is affected by the direction of combustion products to the exhaust of gas turbine. Due to the alignment which is radially mounted on the high pressure module of gas turbine, the discharge nozzle directed towards the high pressure turbine to accelerate hot exhaust to produce thrust as described by Newton's third law of motion. The amount of thrust produced by the engine depends on the mass flow rate through the engine, the exit velocity of the flow, and the pressure at the exit of the engine.

Figure 14: Discharge nozzle of DLE Combustor

(Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual*)

The parameters of concern in modeling the discharge nozzle are material and geometry. The materials used in the discharge nozzle are **Hastelloy X, Haynes 230,** and **Haynes 214**. There are several exhaust area used such as 18000mm^2, 20250 mm^2 and 22500 mm^2 in order to provide the geometrical comparison in terms of stresses, total deformation, velocity and total heat flux. The impact of the structure on the discharge nozzle is measured using ANSYS 11.0 software. The main structure that affected by these two parameters are von misses stress, total deformation and total heat flux.

2.2.1 Stresses

The Von Mises Stress provides a measure of the shear, or distortional, stress in the material. It is used to predict yielding of materials under any loading condition from results of simple uniaxial tensile tests. The same goes with the stress intensity which is to measure the area with high stress concentration. The stresses tend to cause yielding in metals. Yielding begins when the elastic energy of distortion reaches a critical value. The material starts to yield, when σ_1 reaches the yield strength of the material σ_Y.

2.2.2 Total Deformation

The deformation field results from a stress field induced by applied forces or is due to changes in the temperature field inside the body. Higher temperature and stresses can cause material to plastically deform, undergo creep over time. Creep forms due to long term exposure to high level stress and heat. Creep increases with temperature. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function. The temperature range in which creep deformation may occur differs in various materials.

2.2.3 Total Heat Flux

Heat flux or thermal flux is the rate of heat energy transfer through a given surface. Heat flux is the heat rate per unit area. In SI units, heat flux is measured in W/m^2. Heat rate is a scalar quantity, while heat flux is a vector quantity. The measurement of heat flux is done by measuring a temperature difference over a piece of material with known thermal conductivity. Critical heat flux describes the thermal limit of a phenomenon where a phase change occurs during heating.

2.3 Material used for Gas Turbine Combustor

The discharge nozzle operated at 850 to 950 Kelvin range of temperature. The general material used in the combustor is Hastelloy X. The discharge nozzle service life or cycle usage can be improved by good material selection.

There are three materials selected in order to measure the service life based on stress, total deformation and total heat flux. The best material will have the lowest stress, deformation and heat flux on the discharge nozzle model.

The present invention of gas turbine combustor made of a Nickel base alloy having a resistance of thermal fatigue. Combustor of gas turbine usually shaped by cold working from sheet materials which in turn are formed by hot working from ingot of alloy. The alloy used as the material of gas turbine combustor. It must have good hot workability and cold workability. In addition, the material must have high resistance to thermal fatigue because it is subjected to repeated heat cycle consisting of heating by hot combustion gas and subsequent cooling.

2.3.1 Hastelloy X

Hastelloy X is recommended in high temperature application because it has unusual resistance to oxidizing, reducing and neutral atmosphere. It is a common material for the combustor. The combustors made by this alloy were still in good condition after operating for 8700 hours at 2150°F or 1177°C. Hastelloy X is a nickel base alloy that possess and oxidation resistance up to 2200°F. It has excellent formin and welding characteristic. It can be forged due to good ductility. The melting range is 1260-1355°C

Chemical Composition of Hastelloy X

Table 2: Chemical Composition of Hastelloy X

(High Temperature Metals, *Hastelloy X Technical Data.* 12th July 2011

<http://www.hightempmetals.com/techdata/hitempHastXdata.php>)

Element	Min (wt %)	Max (wt %)
Molybdenum	8.00	10.0
Chromium	20.5	23.0
Iron	17.0	20.0
Tungsten	0.20	1.00
Cobalt	0.50	2.50
Carbon	0.05	0.015
Silicon	--	1.00
Manganese	--	1.00
Boron	--	0.01
Phosphorus	--	0.04
Sulfur	--	0.03
Nickel	Remainder	

Physical Properties of Hastelloy X

Table 3: Physical Properties of Hastelloy X

(High Temperature Metals, *Hastelloy X Technical Data.* 12th July 2011

<http://www.hightempmetals.com/techdata/hitempHastXdata.php>)

Mass Density	8.22 g/cm^3
Yield Strength	339 MPa
Ultimate Tensile Strength	743 MPa
Young's Modulus	165 GPa
Thermal Conductivity	27.4 W/(m K)
Specific Heat	477 J/(kg c)

2.3.2 Haynes 230

HAYNES 230 alloy can be utilized at temperatures as high as 2100°F (1150°C) for continuous service. It is a common material used for combustors. It has outstanding resistance for prolonged exposures, premier resistance to nitriding environment and excellent long term thermal stability. Haynes 230 has excellent forming and welding characteristic. The melting range is 1290-1375°C.

Chemical Composition of Haynes 230

Table 4: Chemical Composition of Haynes 230
(High Temperature Metals, *Haynes 230 Technical Data*. 12th July 2011
<http://www.hightempmetals.com/techdata/hitempHaynes230data.php>)

Element	Min (wt %)	Max (wt %)
Carbon	0.05	0.15
Manganese	0.30	1.00
Silicon	0.25	0.75
Phosphorus	--	0.03
Sulfur	--	0.015
Chromium	20.00	24.00
Cobalt	--	5.00
Iron	--	3.00
Aluminum	0.20	0.50
Titanium	--	0.10
Boron	--	0.015
Copper	--	0.50
Lanthanum	0.005	0.05
Tungsten	13.00	15.00
Molybdenum	1.00	3.00
Nickel	Remainder	

Physical Properties of Haynes 230

Table 5: Physical Properties of Haynes 230

(High Temperature Metals, *Haynes 230 Technical Data.* 12th July 2011

<http://www.hightempmetals.com/techdata/hitempHaynes230data.php>)

Mass Density	8.97 g/cm^3
Yield Strength	390 MPa
Ultimate Tensile Strength	885 Mpa
Young's Modulus	211 Gpa
Thermal Conductivity	8.9 W/(m K)
Specific Heat	397J/(kg c)

2.3.3 Haynes 214

HAYNES 214 alloy is a nickel-chromium-aluminum-iron alloy designed to provide the optimum in high-temperature oxidation resistance for a wrought austenitic material. It is a common material used for combustors. It exhibits resistance to oxidation at temperatures as high as 2100°F (1150°C). The melting range is 1355-1400°C.

Chemical Composition of Haynes 214

Table 6: Chemical Composition of Haynes 214

(High Temperature Metals, *Haynes 214 Technical Data*, 12th July 2011

<http://www.matweb.com/search/datasheet.aspx?matguid=16b057206ce6420dadcb60b1576ca0ae&ckck=1>)

Element	Composition (wt %)
Aluminum	4.5
Boron	0.01
Carbon	0.05
Chromium	16
Iron	3
Manganese	0.50
Silicon	0.2
Nickel	75
Yttrium	0.01
Zirconium	0.10

Physical Properties of Haynes 214

Table 7: Physical Properties of Haynes 214

(High Temperature Metals, *Haynes 214 Technical Data*, 12th July 2011

<http://www.matweb.com/search/datasheet.aspx?matguid=16b057206ce6420dadcb60b1576ca0ae&ckck=1>)

Mass Density	8.05 g/cm^3
Yield Strength	565 MPa
Ultimate Tensile Strength	960 Mpa
Young's Modulus	218 Gpa
Thermal Conductivity	12.0 W/(m K)
Specific Heat	452J/(kg c)

2.4 Effect of Geometrical Change on flow velocity at Discharge Nozzle Exhaust

The geometrical change is the main factor that affects the flow velocity of the discharge nozzle to the turbine. One of the important parameter is volumetric flow rate. The volumetric flow rate in fluid dynamics is the volume of fluid which passes through a given surface per unit time in cubic meters per second [m^3/s] in SI units and it is represented by the symbol Q.

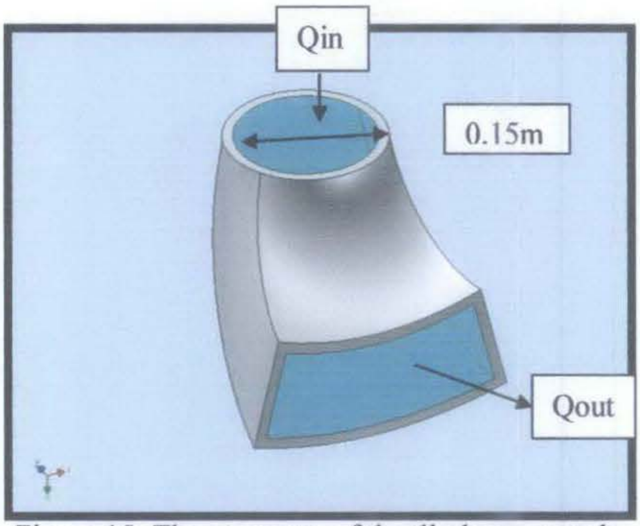


Figure 15: The geometry of the discharge nozzle

The volumetric flowrate,

Qin = Qout

Qin = A1(m^2) x V1(m/s)

Qout = A2(m^2) x V2(m/s)

To calculate Qin;

Discharge Nozzle inlet area, A1 is constant with diameter, D of 0.15 meter.

$$A1 = \pi D^2/4$$

$$= 3.14 \times 0.15^2/4$$

$$= 0.0177\ m^2$$

Air flows from high pressure compressor to combustors with maximum continuous speed of 9550 rpm

The velocity entering the discharge nozzle, V1 is:

V1	=	(Diameter of Gas Turbine compressor/2) x (9550 rpm x ($2\pi/60$)
	=	(2.18/2) x (9550 rpm x ($2\pi/60$)
	=	1090.08 m/s

The geometrical area of the discharge nozzle exhaust is varied with 18000mm^2, 20250 mm^2, and 22500 mm^2.The velocity of three different discharge nozzle exhaust area can be measured based on the formula.

CHAPTER 3
METHODOLOGY

3.1 Milestone for FYP 1

Table 8: Milestone of FYP 1

NO	DETAIL/WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Discussion (Identifying Project Scope)														
2	Research and Preliminary Report														
3	Submission of Preliminary Report														
4	Project Work Continues														
5	Submission of Progress Report														
6	Seminar														
7	Project Work Continues														
8	Submission of Interim Report Final Draft														
9	Oral Presentation														

3.2 Milestone for FYP II

Table 9: Milestone FYP 2

NO	DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continues															
2	Submission of Progress Report															
3	Project Work Continues															
4	Pre EDX															
5	Submission of Draft Report															
6	Submission of Dissertation (soft bound)															
7	Submission of Technical Paper															
8	Oral Presentation															
9	Submission of Dissertation (hard bound)															

3.3 Project flow

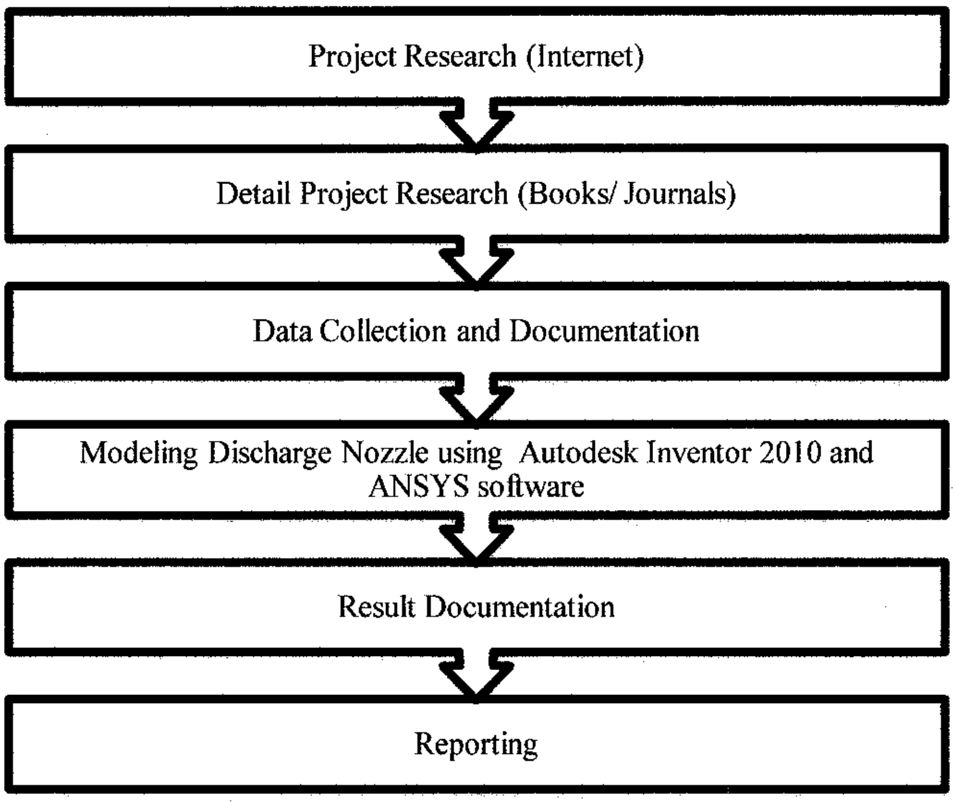


Figure 16: Project Flow

The project work started with preliminary research on the online resource to familiarize with the technology and current issues related. The project continues with detail research by books and journals. Then the data was collected based on the research and reliable journal sources before proceed with modeling discharge nozzle. Then, the project continues with the familiarizing with ANSYS software. The preliminary modeling phase started by generating actual model of the discharge nozzle with Hastelloy X material. The stress, deformation, displacement and heat flux analyzed through the software simulation and report. The preliminary modeling result is then documented in the report. The project continues by changing the modeling parameter such as geometry and material. Three materials are compared with Hastelloy X which are Haynes 240 and Haynes 214. The comparison is made by simulating different material in ANSYS 11.0 and measure the von mises stress, deformation and total heat flux.

The modeling and analysis continues by changing the geometry from $0.018m^2$ to $0.02025m^2$ and $0.02250m^2$. This selection is based on the height, H which are 100mm for the original combustor, 90mm and 80mm of combustor exhausts.

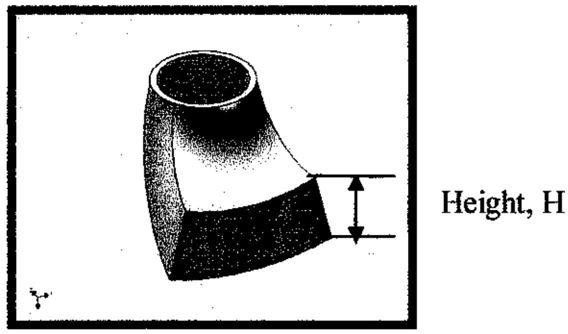


Figure 17: Height Measurement of Discharge Nozzle

3.4 Method of using Autodesk Inventor 2010 software

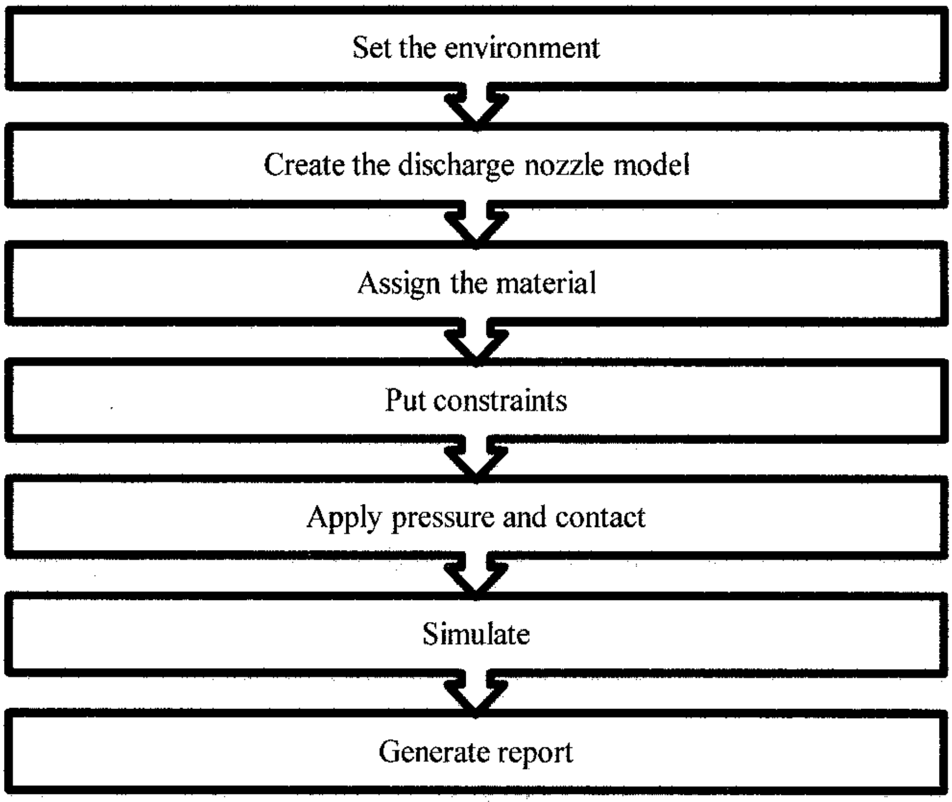


Figure 18: Method of using Autodesk Inventor 2010 software

The objective of using Autodesk Inventor 2010 is to design the discharge nozzle before importing it to ANSYS software. This software has the capability to measure the stress, displacement, strain and safety factor of the model. The design requires setting to different plane in order to design the discharge nozzle. Loft method is used to produce the discharge nozzle before offsetting to the required thickness. For stress analysis, the material can be assigned to measure several parameters such as von mises stress, 1st principal stress, 3rd principal stress, strain, displacement and safety factor. After finished designing in the Autodesk Inventor, the model is exported to ANSYS 11.0 software for further modeling and analysis.

3.5 Method of using ANSYS 11.0 software

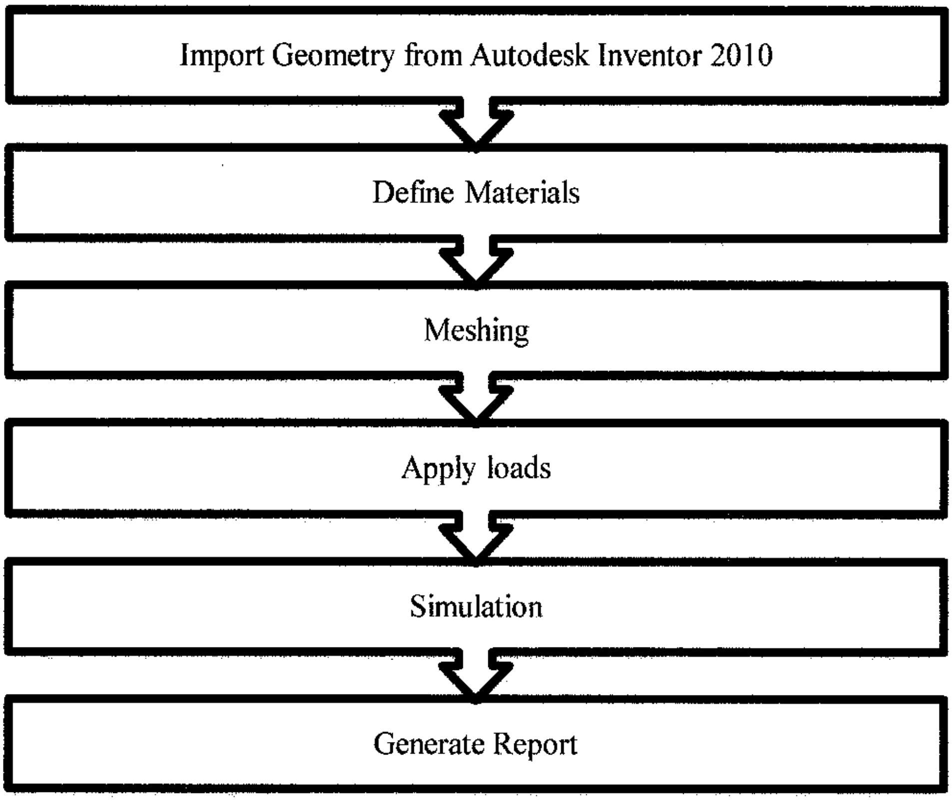


Figure 19: Method of using ANSYS 11.0 software

The objective of using ANSYS is to model and analyze the stress, total deformation and total heat flux of the discharge nozzle after importing it from Autodesk Inventor 2010. The material can be assigned in ANSYS software with the required properties before simulation. Before simulation of results, meshing is required to the model. For the boundary conditions, the temperature of 950°C is applied in the discharge nozzle with pressure of 2Mpa. Lastly, the simulation result of stress, total displacement and total heat flux is obtained by the software.

CHAPTER 4
RESULT AND DISCUSSION

4.1 Impact on Changing the Geometry of the Discharge Nozzle

The geometry is changed based on the exhaust area. The actual exhaust area is 0.0225 m^2. The impact is analyzed by changing the area to 0.02025 m^2 and 0.018 m^2. The objective is to measure the impact to the service life through stress, total deformation and total heat flux on the models which are simulated using ANSYS 11.0 software after designed in Autodesk Inventor Professional 2010. The velocity is also calculated for every type of geometry to identify the highest performance of discharge nozzle. Hastelloy X is used as the material which is constant for every model. The temperature of 950°C is applied in the discharge nozzle with pressure of 2Mpa.

4.1.1 Result Summary

Table 10: Comparison of three discharge nozzle model with different geometry

Model		A	B	C
Exhaust Area(mm^2)		18000	20250	22500 (actual)
Volume (m^3)		1.2032×10^{-3}	1.2634×10^{-3}	1.2792×10^{-3}
Mass (kg)		9.8902	10.385	10.515
Total Deformation (m)	Min	0	0	0
	Max	4.2641×10^{-5}	3.9075×10^{-5}	4.2446×10^{-5}
Von Mises Stress (pa)	Min	1.4631×10^{6}	1.4962×10^{6}	1.7739×10^{6}
	Max	5.5656×10^{7}	4.779×10^{7}	5.0175×10^{7}
	Avg	2.8560×10^{7}	2.4643×10^{7}	2.5974×10^{7}
Stress Intensity (pa)	Min	1.6549×10^{6}	1.7256×10^{6}	2.0071×10^{6}
	Max	6.0877×10^{7}	5.3865×10^{7}	5.7272×10^{7}
	Avg	3.1266×10^{7}	2.7795×10^{7}	2.9640×10^{7}
Total Heat Flux (W/m^2)	Min	1.8877×10^{-8}	1.0464×10^{-8}	1.4637×10^{-8}
	Max	8.8428×10^{-6}	9.9282×10^{-6}	9.0853×10^{-6}
	Avg	4.4308×10^{-6}	4.9693×10^{-6}	4.5500×10^{-6}

The table shows the result of three models of discharge nozzle with different geometry. The objective is to find the model with the good service life which can sustain longer in the combustor. The geometry is compared based on different exhaust area. The lightest model is model A with 9.89kg and model C is the heaviest with 10.515kg. Model A experience the highest total deformation with 4.2641×10^{-5} m followed by model C and model B. The highest Von Mises Stress is discovered in Model A with the average of 2.8560×10^{7} pa. Model B experience the lowest average of Von Mises Stress with 2.4643×10^{7} pa, compared with Model A and Model C. The same goes with the stress intensity. Model A experience the highest intensity of stress with the average of 3.1266×10^{7}pa and followed by model C and Model B. For total heat flux, Model B experiences the highest average of $4.9693\times10^{-6}W/m^2$ followed by Model C and Model A.

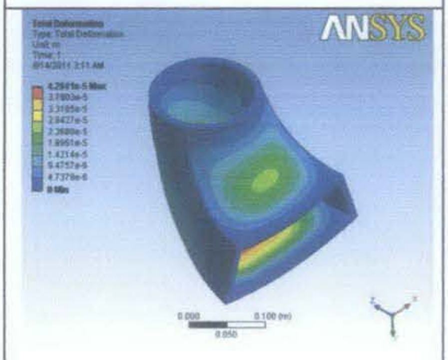
The service life requires the lowest deformation, stress and total heat flux. Based on the result, for the lowest total deformation and the lowest stresses, Model B is desirable. Model B provides the lowest shear, or distortional, stress in the material. The yielding of materials under any loading condition will be less compared to Model A and C. The discharge nozzle in the combustor experience high stress and temperature that tends to cause yielding. The deformation field results from a stress field induced by applied forces or is due to changes in the temperature field inside the body. Higher temperature and stresses can cause material to plastically deform, undergo creep over time. Creep forms due to long term exposure to high level stress and heat. Creep increases with temperature and stress. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function. Low stress and deformation needed to prevent creep. Model B is desirable for this requirement.

But in terms of total heat flux, Model B is inappropriate for the application. The appropriate model is Model A with the lowest total heat flux. Higher temperature can cause material to plastically deform. The lowest total heat flux represents the reduction of temperature difference over a piece of material with known thermal conductivity. Critical heat flux describes the thermal limit of a phenomenon where a phase change occurs during heating. The results show that different size of exhaust area provides different range of deformation, stress and total heat flux.

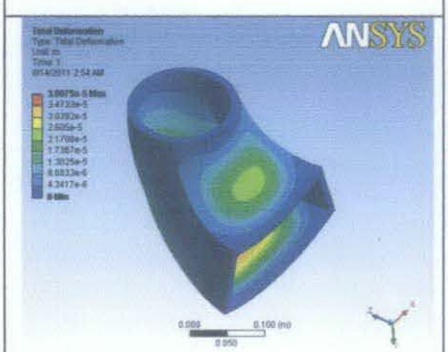
4.1.2 Result Simulation

For total deformation, the simulation results are as follows;

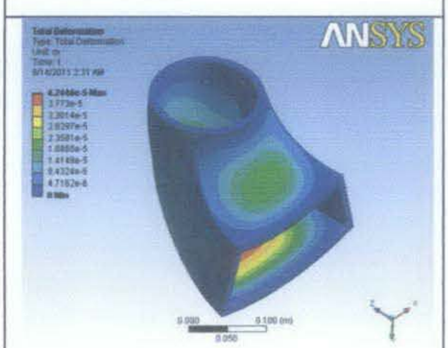
Model A

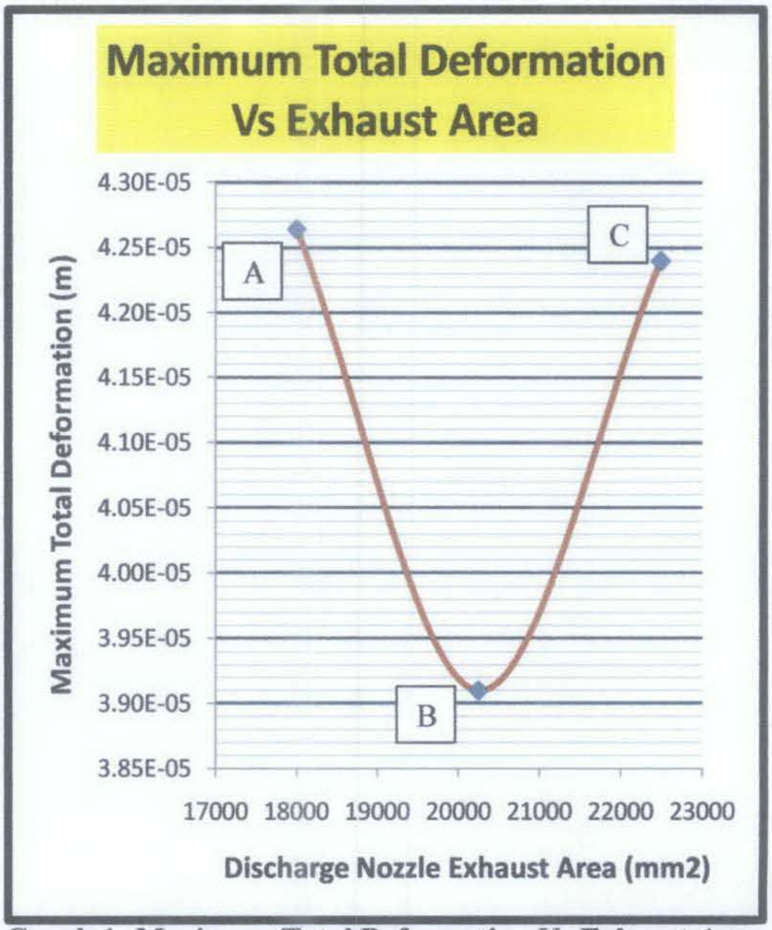


Model B



Model C



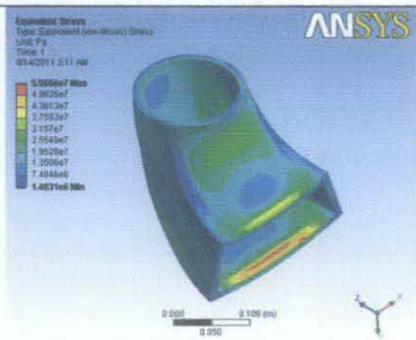


Graph 1: Maximum Total Deformation Vs Exhaust Area

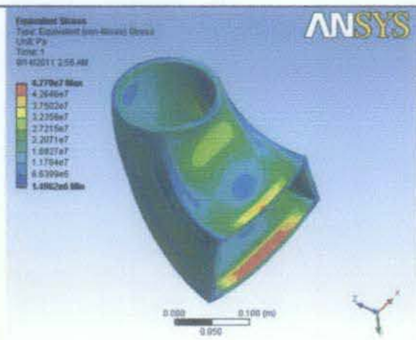
The simulation of Total Deformation is made using ANSYS 11.0 software. The red color indicates the highest deformation region and the blue color indicates the lowest deformation region. Based on the simulation result, Model B has the lowest total deformation compared with Model C and Model A. The simulation result is interpreted into graph. The highest deformation experienced by Model A. Most of the deformation or buckling occurred on the curvature region.

For Equivalent (Von Mises) Stress, the simulation results are as follows;

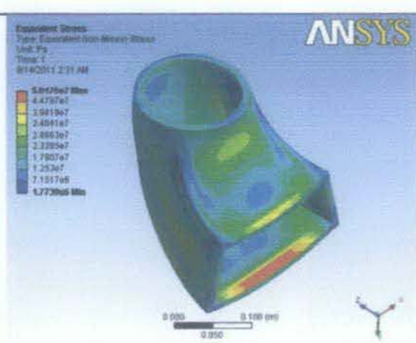
Model A

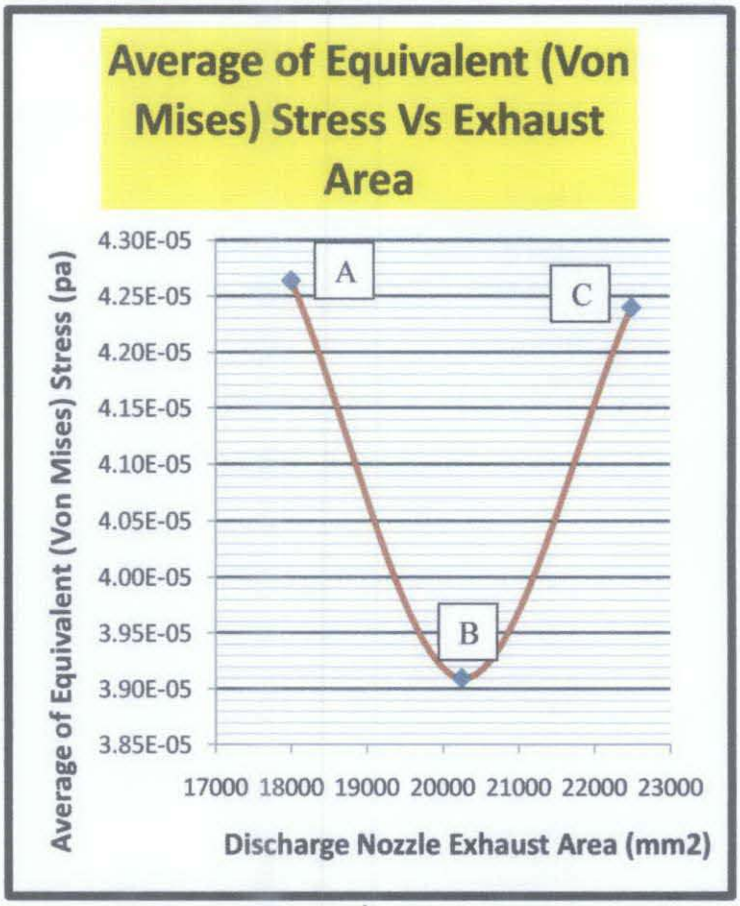


Model B



Model C





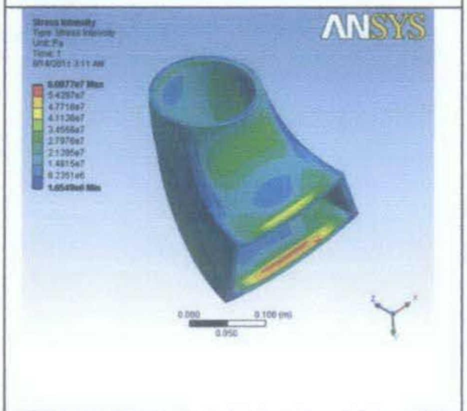
\

Graph 2: Average of Equivalent(Von Mises) Stress Vs Exhaust Area

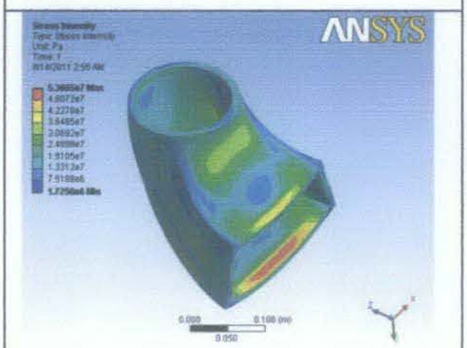
The simulation of Von Mises Stress is made using ANSYS 11.0 software. The red color indicates the highest Von Mises stress region and the blue color indicates the lowest Von Mises stress region. Based on the simulation result, Model B has the lowest Von Mises stress compared with Model C and Model A. The simulation result is interpreted into graph. The highest Von Mises stress experienced by Model A. The highest region for Von Mises stress is at the exhaust area of the discharge nozzle.

For Stress Intensity, the simulation results are as follows;

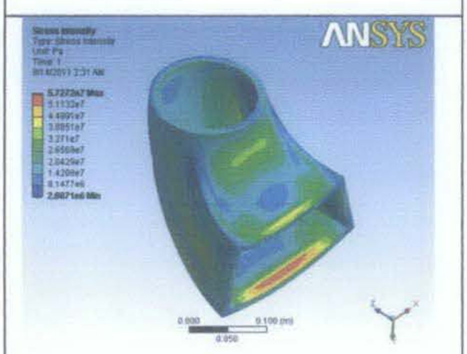
Model A

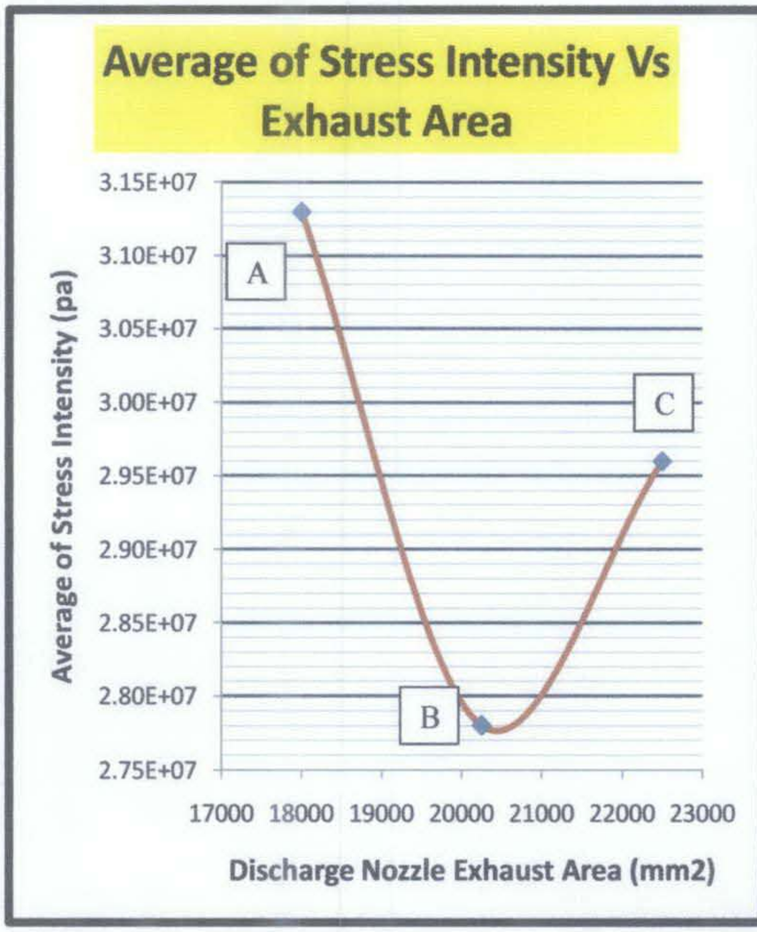


Model B



Model C



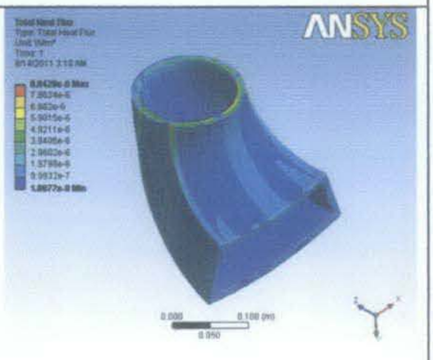


Graph 3: Average of Stress intensity Vs Exhaust Area

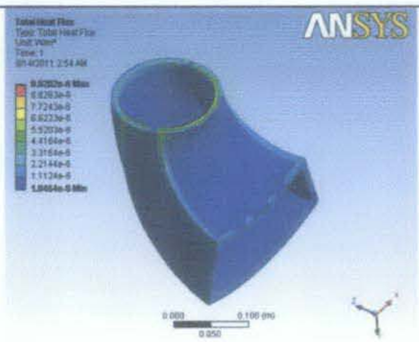
The simulation of Stress Intensity is made using ANSYS 11.0 software. The red color indicates the highest intensity of stress region and the blue color indicates the lowest intensity of stress region. Based on the simulation result, Model B has the lowest stress intensity compared with Model C and Model A. The simulation result is interpreted into graph. The highest intensity of stress experienced by Model A. The highest region for Von Mises stress is at the exhaust area of the discharge nozzle which is the same result as von Mises Stress.

For total heat flux, the simulation results are as follows;

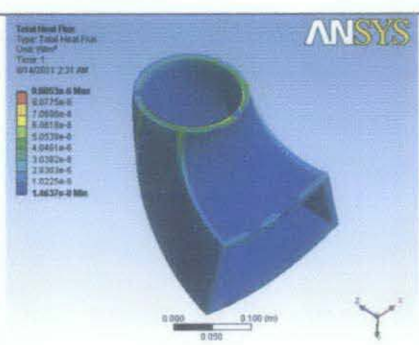
Model A

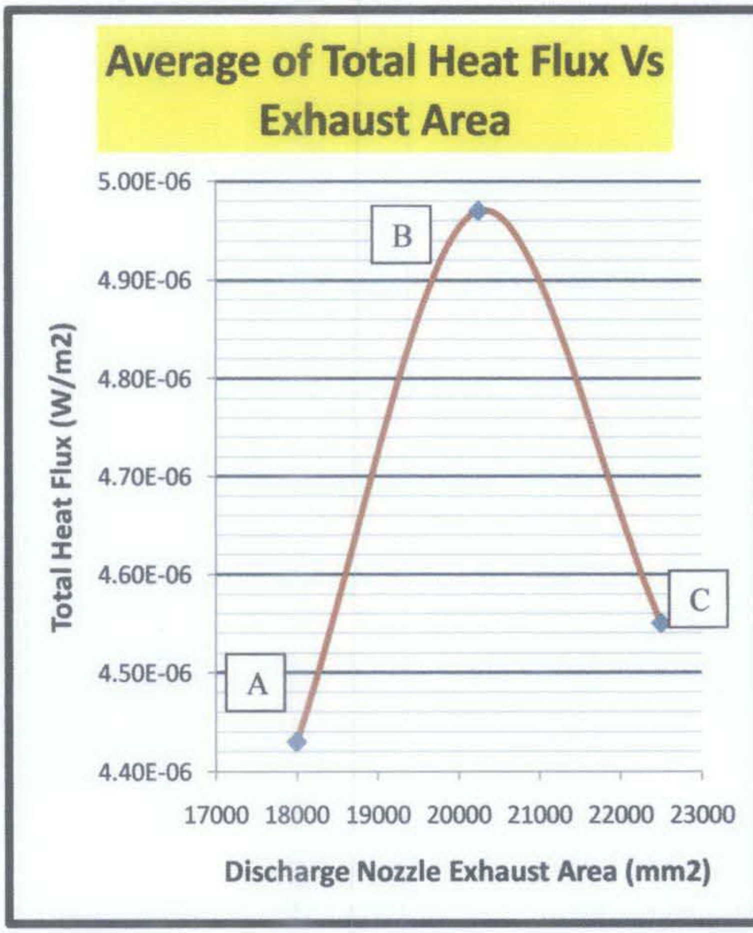


Model B



Model C





Graph 4: Average of Total Heat Flux Vs Exhaust Area

The simulation of Average of Total Heat Flux is made using ANSYS 11.0 software. The red color indicates the highest total heat flux and the blue color indicates the lowest total heat flux region. Based on the simulation result, Model A has the lowest total heat flux compared with Model C and Model B. The simulation result is interpreted into graph. The highest total heat flux experienced by Model B. The highest region for total heat flux occurred at the inlet area of the discharge nozzle when the combustion product entering the discharge nozzle.

The modeling results show the variety of options. Model B is appropriate to satisfy low deformation and low stresses requirement. Model B has a weakness in terms of heat flux compared with others. But the difference is only $0.53x10^{-6}$ W/m^2 which is not very significant. Model A may be appropriate for low total heat flux options but it will results high deformation and high stresses to the discharge nozzle. The higher service life requires low stresses, less total deformation and low total heat flux. Model B will be appropriate for this application.

In actual design, the geometrical changes of the discharge nozzle are not desirable because it will give several impacts on the gas turbine. The geometrical changes will affect the instruments near the combustor, blade, maintainability, and the overall design. But these findings will be a possible way to help Rolls Royce to improve the service life of the discharge nozzle in RB211 Gas Turbine combustor for future design applications.

4.1.3 Velocity Impact resulted from Geometrical Change

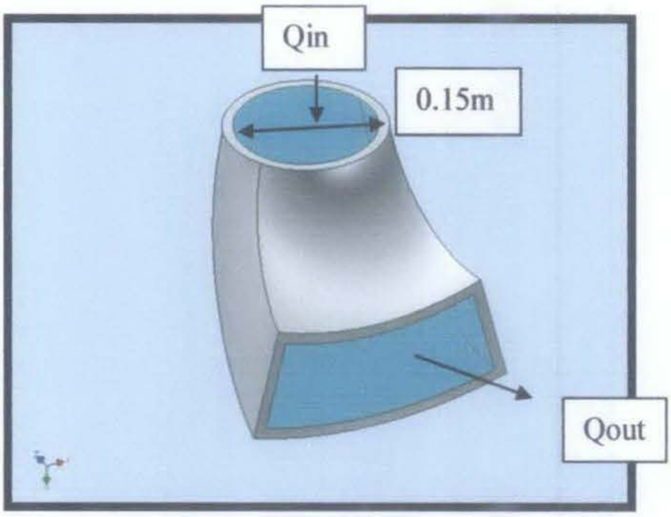


Figure 20: The flow pattern of the discharge nozzle

The volumetric flowrate,

Qin = Qout

Qin = $A1(m^2)$ x $V1(m/s)$

Qout = $A2(m^2)$ x $V2(m/s)$

Discharge Nozzle inlet area, A1 is constant with diameter, D of 0.15 meter.

A1 = $0.0177\ m^2$

Air flows from high pressure compressor to combustors with maximum continuous speed of 9550 rpm

The velocity entering the discharge nozzle, V1 is:

V1 = 1090.08 m/s

.:. The inlet volumetric flow rate, Qin = $0.0177m^2$ x 1090.08 m/s

= $19.29\ m^3/s$

The geometrical area of the discharge nozzle exhaust is varied with 18000mm^2, 20250 mm^2, and 22500 mm^2.The velocity of three different discharge nozzle exhaust area can be measured based on the formula.

Qin	=	Qout
A1 x V1	=	A2 x v2

Model A:

When Exhaust Area of discharge nozzle, A2 = 0.018m^2

0.0177m^2 x 1090.08 m/s	=	0.018 m^2 x V2
V2	=	1071.91 m/s

Model B:

When Exhaust Area of discharge nozzle, A2 = 0.02025m^2

0.0177m^2 x 1090.08 m/s	=	0.02025 m^2 x V2
V2	=	952.81 m/s

Model C:

When Exhaust Area of discharge nozzle, A2 = 0.0225m^2

0.0177m^2 x 1090.08 m/s	=	0.0225 m^2 x V2
V2	=	657.53 m/s

When the area is increasing, the flow velocity reduced.

When area reduced, **Model A<Model B<Model C**

The flow velocity increased, **Model A>Model B>Model C**

The highest velocity experienced by **Model A** at the discharge nozzle exhaust is desirable to increase the speed for High Pressure Turbine.

4.2 Impact on Changing the Material of the Discharge Nozzle

Three materials are chosen which are Hastelloy X, Haynes 230 and Haynes 214 to measure the impact to the service life through stress, total deformation and total heat flux on the models which are simulated using ANSYS 11.0 software after designed in Autodesk Inventor Professional 2010. The temperature of 950°C is applied in the discharge nozzle with pressure of 2Mpa. The preferred material must have the lowest stress, deformation and total heat flux. This is important to ensure the longest performance of the discharge nozzle during the service.

4.2.1 Result Summary

Table 11: Comparison of three discharge nozzle model with different material

Material		Hastelloy X	Haynes 230	Haynes 214
Exhaust Area(mm^2)		22500	22500	22500
Volume (m^3)		1.2792×10^{-3}	1.2792×10^{-3}	1.2792×10^{-3}
Mass (kg)		10.515	11.474	10.298
Total Deformation (m)	Min	0	0	0
	Max	4.2446×10^{-5}	3.3488×10^{-5}	3.2271×10^{-5}
Von Mises Stress (pa)	Min	1.7739×10^{6}	1.5421×10^{6}	1.6554×10^{6}
	Max	5.0175×10^{7}	4.9458×10^{7}	4.9802×10^{7}
	Avg	2.5974×10^{7}	2.5500×10^{7}	2.5729×10^{7}
Stress Intensity (pa)	Min	2.0071×10^{6}	1.7553×10^{6}	1.8781×10^{6}
	Max	5.7272×10^{7}	5.6304×10^{7}	5.6774×10^{7}
	Avg	2.9640×10^{7}	2.9030×10^{7}	2.9326×10^{7}
Total Heat Flux (W/m^2)	Min	1.4637×10^{-8}	7.0542×10^{-9}	5.4823×10^{-9}
	Max	9.0853×10^{-6}	3.1634×10^{-6}	4.1498×10^{-6}
	Avg	4.5500×10^{-6}	1.5852×10^{-6}	4.1552×10^{-6}

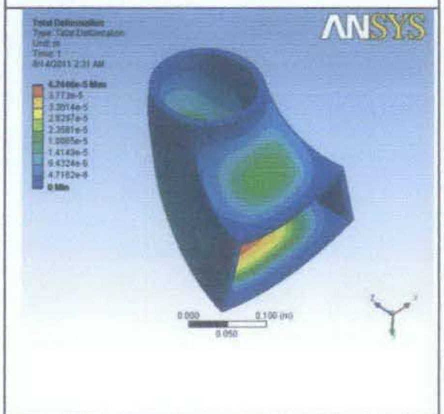
The table shows the result of three models of discharge nozzle with different geometry. The objective is to find the model with the good service life which can sustain longer in the combustor. Three materials are compared which are Hastelloy X, Haynes 230 and Haynes 214. The lightest model is Haynes 214 with 10.298kg and Haynes 230 is the heaviest with 11.474kg. Hastelloy X experiences the highest total deformation with 4.2446×10^{-5} m followed by Haynes 230 and Haynes 214. The highest Von Mises Stress is discovered in Hastelloy X with the average of 2.5974×10^{7}pa. Haynes 230 experiences the lowest average of Von Mises Stress with 2.55×10^{7}pa, compared with others. The same goes with the stress intensity. Hastelloy X experiences the highest intensity of stress with the average of 2.9640×10^{7}pa and followed by Haynes 214 and Haynes 230. For total heat flux, Hastelloy X experiences the highest average of $4.5500 \times 10^{-6} W/m^2$ followed by Haynes 214 and Haynes 230.

Service life is the expected lifetime or acceptable period of use in service. The service life requires the lowest deformation, stress and total heat flux. Based on the result, for the lowest total deformation, Haynes 214 is desirable. The deformation field results from a stress field induced by applied forces or is due to changes in the temperature field inside the body. Haynes 214 provides the lowest shear, or distortional, stress in the material. The yielding of materials under any loading condition will be less compared to Haynes 230 and Hastelloy X. But for the lowest intensity of stress and Von Mises stress, Haynes 230 is preferable rather than Haynes 214.The discharge nozzle in the combustor experiences high stress and temperature that tends to cause yielding. Higher temperature and stresses can cause material to plastically deform, undergo creep over time. Creep forms due to long term exposure to high level stress and heat. Creep increases with temperature and stress. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function. Low stress and deformation needed to prevent creep. The highest stress and deformation occurred in Hastelloy X will increase the formation of creep in the combustor. For total heat flux, Hastelloy X is inappropriate for the application. The appropriate material is Haynes 230 with the lowest total heat flux. Higher temperature can cause material to plastically deform. The lowest total heat flux represents the reduction of temperature difference over a piece of material with known thermal conductivity. Heat transfer across materials of high thermal conductivity occurs at a faster rate compared with materials of low thermal conductivity. Haynes 230 has the lowest thermal conductivity with 8.9 W/ (mK) compared with Hastelloy X with 27.4 W/(mK). Critical heat flux describes the thermal limit of a phenomenon where a phase change occurs during heating.

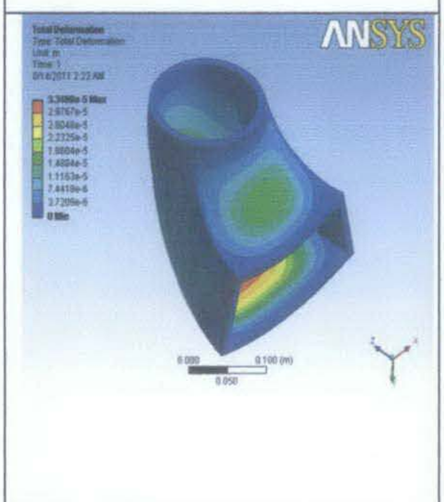
4.2.2 Result Simulation

For total deformation, the simulation results are as follows;

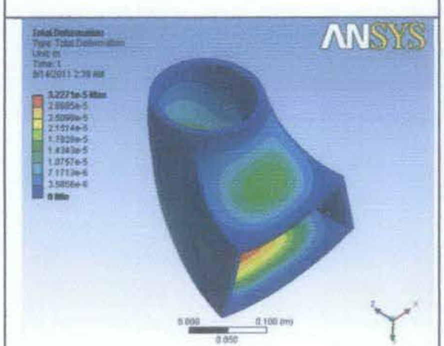
Hastelloy X

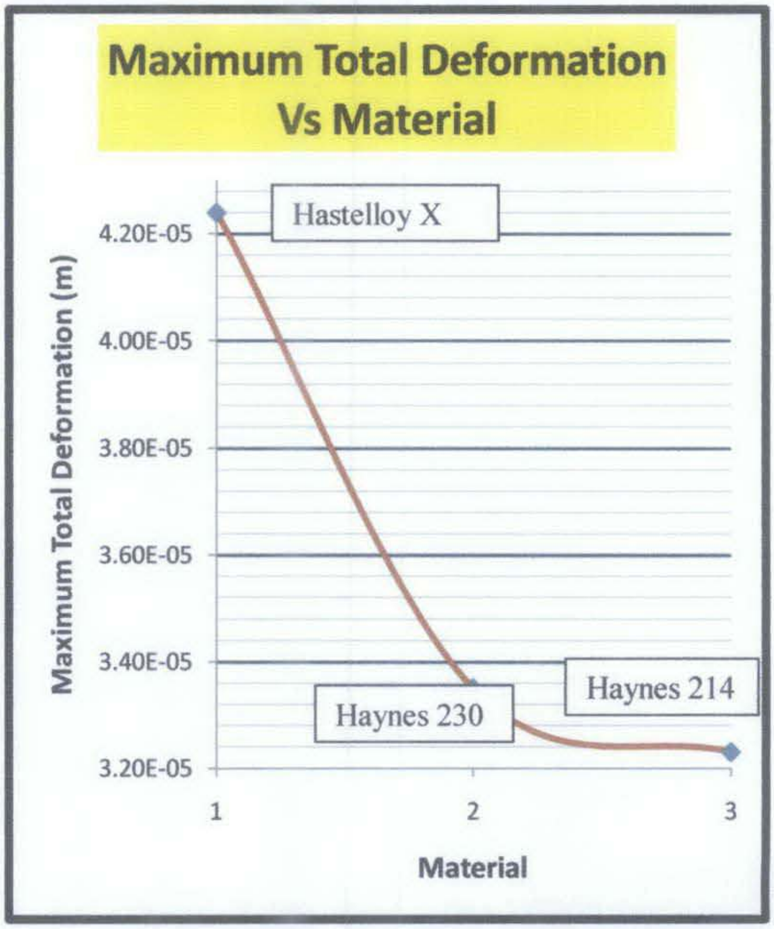


Haynes 230



Haynes 214



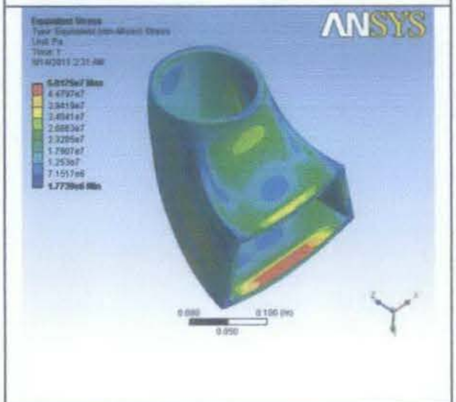


Graph 5: Maximum Total Deformation Vs Material

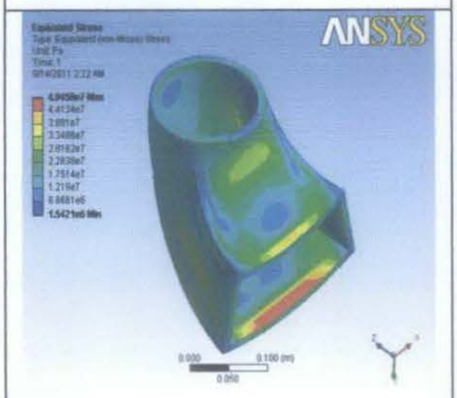
The simulation of Total Deformation is made using ANSYS 11.0 software. The red color indicates the highest deformation region and the blue color indicates the lowest deformation region. Based on the simulation result, Haynes 214 has the lowest total deformation compared with Haynes 230 and Hastelloy X. The simulation result is interpreted into graph. The highest deformation experienced by Hastelloy X. Most of the deformation or buckling occurred on the curvature region.

For Equivalent (Von Mises) Stress, the simulation results are as follows;

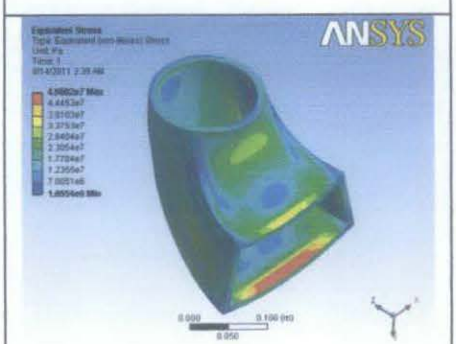
Hastelloy X

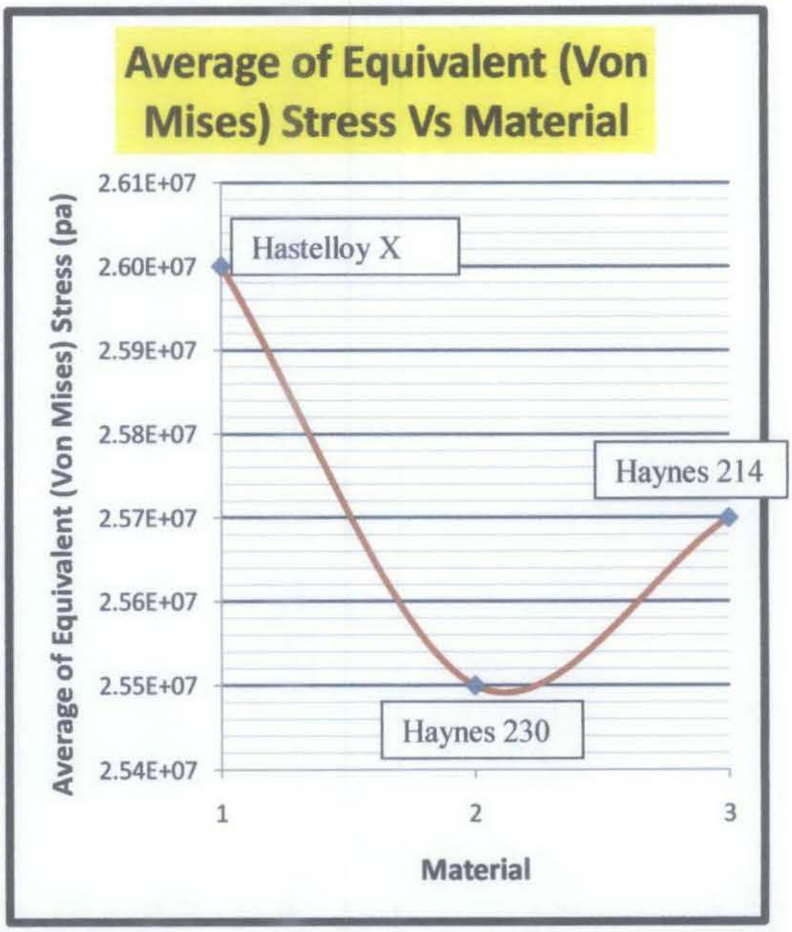


Haynes 230



Haynes 214



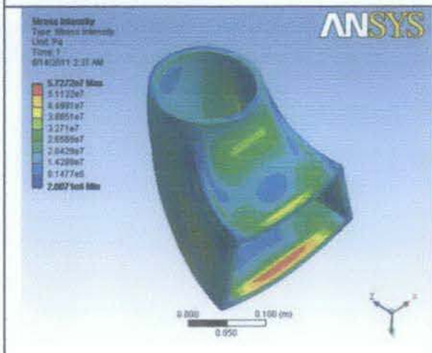


Graph 6: Average of Equivalent(Von Mises) Stress Vs Material

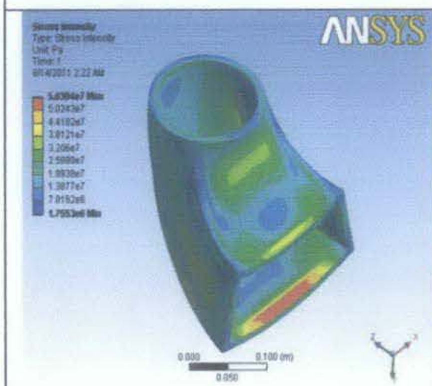
The simulation of Von Mises Stress is made using ANSYS 11.0 software. The red color indicates the highest Von Mises stress region and the blue color indicates the lowest Von Mises stress region. Based on the simulation result, Haynes 230 has the lowest Von Mises stress compared with Haynes 214 and Hastelloy X. The simulation result is interpreted into graph. The highest Von Mises stress experienced by Hastelloy X. The highest region for Von Mises stress is at the exhaust area of the discharge nozzle.

For Stress Intensity, the simulation results are as follows;

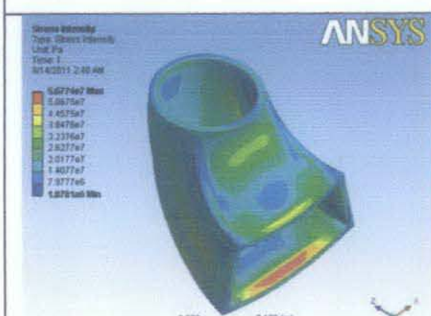
Hastelloy X

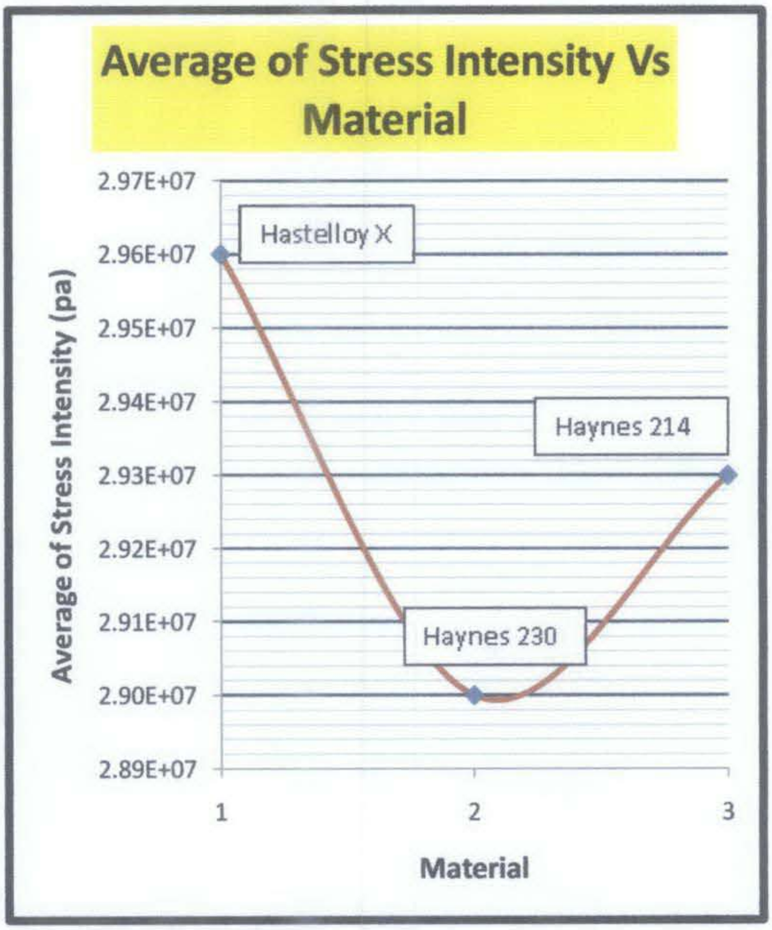


Haynes 230



Haynes 214



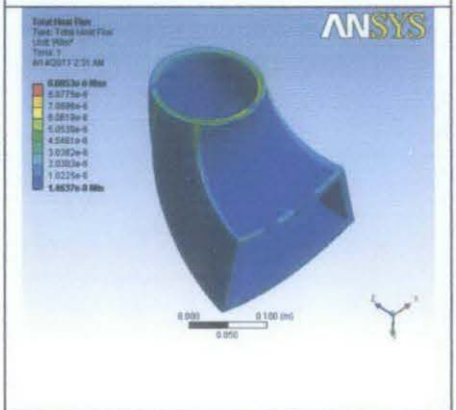


Graph 7: Average of Stress intensity Vs Material

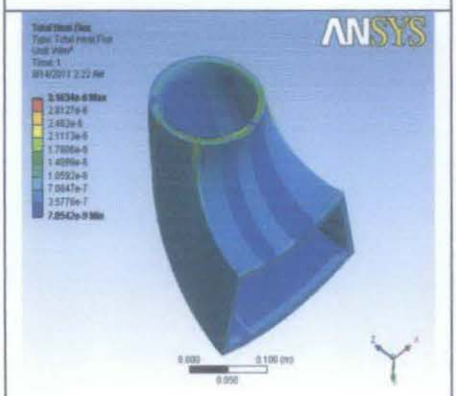
The simulation of Stress Intensity is made using ANSYS 11.0 software. The red color indicates the highest intensity of stress region and the blue color indicates the lowest intensity of stress region. Based on the simulation result, Haynes 230 has the lowest stress intensity compared with Haynes 214 and Hastelloy X. The simulation result is interpreted into graph. The highest intensity of stress experienced by Hastelloy X. The highest region for Von Mises stress is at the exhaust area of the discharge nozzle which is the same result as von Mises Stress.

For total heat flux, the simulation results are as follows;

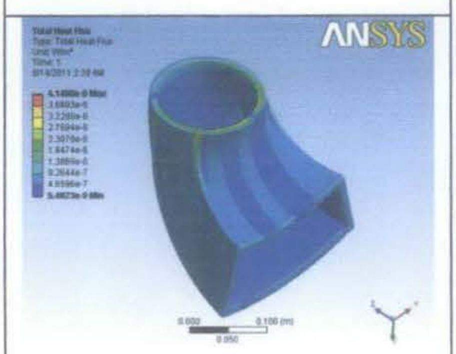
Hastelloy X

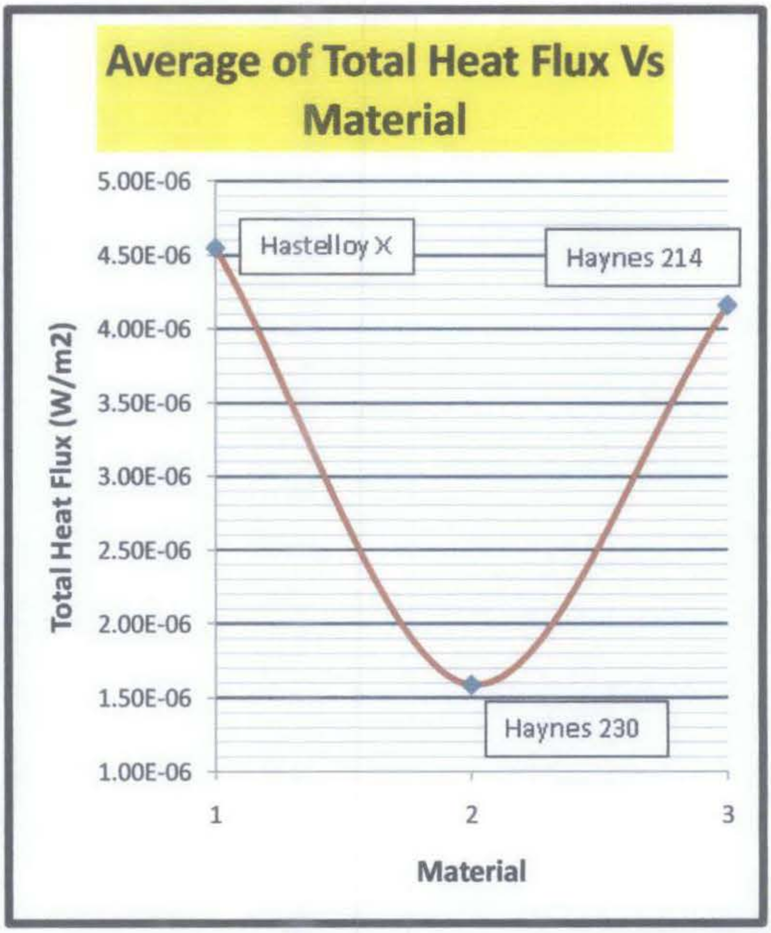


Haynes 230



Haynes 214





Graph 8: Average of Total Heat Flux Vs Material

The simulation of Average of Total Heat Flux is made using ANSYS 11.0 software. The red color indicates the highest total heat flux and the blue color indicates the lowest total heat flux region. Based on the simulation result, Haynes 230 has the lowest total heat flux compared with Haynes 214 and Hastelloy X. The simulation result is interpreted into graph. The highest total heat flux experienced by Hastelloy X. The highest region for total heat flux occurred at the inlet area of the discharge nozzle when the combustion product entering the discharge nozzle.

From the result, it shows that Haynes 230 is the appropriate material compared with Hastelloy X and Haynes 214 as the material used in the discharge nozzle because Haynes 230 has the lowest Von Mises Stress, Intensity of Stress and total heat flux. The only weakness is in total deformation. But the difference is only $0.12x10^{-5}$m which is not significant when compared with the Haynes 214. Hastelloy X is not appropriate in the application of discharge nozzle material due to high stresses, total heat flux and total deformation. Haynes 230 will be the best options compared with Hastelloy X and Haynes 214.

Haynes 230 will be the best alternative material for the discharge nozzle in Rolls Royce RB211 Gas Turbine combustor for Dry Low Emission system. This is the possible improvement that can be made for better cycle usage and life spent in the combustion environment. Haynes 230 is suitable to sustain within the extreme temperature limit due to low thermal conductivity and high yield strength.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The objectives are achieved in this project which are to model and analyze the discharge nozzle in DLE Combustor in Industrial Rolls Royce RB211 Gas Turbine, to do FEA modeling and analyze stress, total heat flux, and total deformation in the discharge nozzle structure by changing the geometry and material and to find alternative material for the discharge nozzle. This project has covered several scopes which are modeling and analysis of Dry Low Emission Combustor Discharge Nozzle Structure for Rolls Royce RB211 Gas Turbine, FEA modeling and analyzing stresses, total heat flux and deformation in the discharge nozzle structure for Rolls Royce RB211 Gas Turbine by changing the geometry and material, possible improvement in terms of material for the discharge nozzle by focusing on the service life and lastly alternative material for the discharge nozzle of RB211 Gas Turbine. The service life is measured in terms of stress, deformation and total heat Flux. Rolls Royce requires low deformation, low stress and less total heat flux of the discharge nozzle to ensure better service life or cycle usage.

The geometry is changed by varying the exhaust area of the discharge nozzle which is calculated based on height setting. The result shows that, when the exhaust area is reduced, the velocity will be increasing. But the stresses, total heat flux and total deformation are varied in terms of geometry. Based on the results, Model B is appropriate for the application with the exhaust area of 2025mm^2. This model is chosen due to several criteria such as low stress, low total deformation and the total heat flux which is high but not significant compared to other model. It is the best options to give the better service life for discharge nozzle in Rolls Royce RB211 Gas Turbine Combustor. The geometrical changes will give several impacts to the overall design of Rolls Royce Gas Turbine. But these findings will help Rolls Royce for the future design of the discharge nozzle for Dry Low Emission combustor. The impact of changing the materials are also measured using ANSYS 11.0 modeling simulation. Three materials are chosen which are

Hastelloy X, Haynes 214 and Haynes 240. This is the common material used for combustors in gas turbine. The material is compared in terms of Von Mises stress, Stress Intensity, deformation and total heat flux. The results show Haynes 230 is the best material for the discharge nozzle. It has low stresses and low heat flux compared with other materials. In terms of total deformation, it has the higher total deformation compared with Haynes 214 but the value is not very significant. Hastelloy X is not appropriate for the application due to higher stress, higher total deformation and higher total heat flux compared with Haynes 214 and Haynes 230. Haynes 230 will be the best alternative material that can be used for the discharge nozzle in Rolls Royce RB211 Dry Low Emission combustor. For the future work expansion and continuation suggestion, new design of the discharge nozzle should be made in order to increase the performance of the discharge nozzle in Rolls Royce RB211 Dry Low Emission combustor. The project must be focusing more on identifying and reducing the losses that influence the required output which is occurred in the discharge nozzle and help increasing the speed of high pressure turbine in DLE Gas Turbine.

REFERENCES

Arthur H. Lefebre. "Gas Turbine Combustion", *Taylor and Francis founded 1798 Second Edition*

Associate Professor D Kretschmer, *Department of Mechanical Engineering University Laval, Quebec, Canada*, "Gas Turbine Fuels and Their Influence on combustion" Published in October 1986

"A journal of Gas Turbine Material," *Gas Turbine Combustor Material.* <http://www. freepatentsonline.com / 4621499.pdf>

"A journal of Haynes 214 Alloy", 12 August 2011 <http://www.haynesintl.com/pdf/ h3008.pdf>

Charles E. Baukal, Jr., *PHD Petroleum Engineering John Zinc Company LLC, Tulsa, Oklohama* "Heat Transfer in Industrial Combustion", pg 475

High Temperature Metals, *Haynes 230 Technical Data.* 12th July 2011<http://www.hightempmetals.com/techdata/hitempHaynes230data.php>

High Temperature Metals, *Hastelloy X Technical Data.* 12th July 2011<http://www.hightempmetals.com/techdata/hitempHastXdata.php>

High Temperature Metals, *Haynes 214 Technical Data*, 12th July 2011 <http://www.matweb.com/search/datasheet.aspx?matguid=16b057206ce6420dadcb60b1576ca0ae&ckck=1>

L.B Davis and S.H. Black ,GE Power Systems Schenectady, New York, *Dry Low NOx Combustion System for GE Heavy Duty Gas Turbine* <http://www.gepower.com/prod_serv/products/tech_docs/en/downloads/ger3568g.pdf>

Phillip P. Walsh, *Bsc. FRAe, CEng, Head of Performance and Engine System Rolls Royce plc* and Paul Fletcher, *MA(OXON), MRAeS, CEng, Manager of Preliminary Design Energy Bussiness Rolls Royce plc,* "Gas Turbine Performance",1988

The engineering Toolbox, *Stoichiometric combustion* <http://www.engineeringtoolbox.com/stoichiometric-combustion-d_399.html>

United Nations (1998). *Kyoto Protocol to the United Nation Framework Convention on Climate Change*,28 July 2010 <http://unfccc.int/resource/docs/convkp/kpeng.pdf>

Rolls Royce, "A manual for RB211 Training," *Rolls Royce RB211-24 G Gas Generator Training Manual* : 13-17

Rolls Royce, "A manual for SHELL Malampaya," *RB211 Gas Turbine Manual of SHELL MALAMPAYA*

Rolls Royce,2004 "A manual for Rolls Royce," *Rolls Royce Virtual Communication Environment*