Development and Analysis of a Gas Turbine to Run on Syngas from a Mui-Basin Coal Gasifier Using CFD: A Review

Agatha Mbeni Muinde and Eng. Dr. Hiram Ndiritu and Dr. Benson Gathitu

Abstract—The global energy demand has been increasing over the years and is still expected to increase by 25% from 2014 to 2040. The rise is demand is being accelerated by economic growth and industrialization of developing countries in Africa and also due to the projected global population growth from 7.2 billion in 2014 to 9 billion in 2040. Fossil fuels have been the major source of global energy, by the end of the 20^{th} century they accounted for 85% of the total energy consumed. Combustion of the fossil fuels to produce energy leads to the production of greenhouse gases. Hence there is a need for clean, cheap and reliable source of energy to meet the rise in demand.

Coal is a cheap yet dirty source of energy and it is being used to generate 41.5% of the world electricity and to meet 26.5% of global primary energy needs. Technologies have been developed to reduce emissions from coal power plants such as flue gas clean up technologies, clean coal technologies, and the use of alternative fuel like natural gas. Clean coal technologies include; pressurized fluidized bed combustion, carbon capture and storage and Integrated Gasification Combined Cycle (IGCC).

This review paper deals with the ways being used to increase the performance and efficiency of a syngas turbine for power generation. Increasing the thermal efficiency is one of the ways of increasing the gas turbine performance while loss reduction is also essential.

Keywords—Efficiency, Gas turbine, Syngas, TTT

I. INTRODUCTION

THE global energy demand has been on a steady rise and is expected to be more rapid as economic growth peaks in countries of Africa. The energy demand is expected to rise by 25% from 2014 to 2040. This is due to the projected global population growth from 7.2 billion in 2014 to 9 billions in 2040 [1] and due to the expected growth in GDP.

The energy demand in Kenya can be shown clearly by the electricity demand. As at 2013 the electricity demand was at 1,191 MW and it was projected to increase to 15,000 MW by 2030 [2]. The rise in demand will be caused by; iron ore smelting, standard gauge and light rail, ICT parks that are being constructed, the LAPSET project, rural electrification programs, school computer programs [3]. The government in preparation for the rise in demand started the 5000+ MW 40 months generation program to meet the expected rise in demand. The program is expected to lower the cost electricity from US$ cents 19.78 to 10.43 for domestic and from US$ cents 14.14 to 9.00 for industrial/commercial, to increase electricity supply, access, reliability and safety of services, to reduce lower system losses pass-over cost to customers and to spur economic production, employment, investments and social development [4].

Fossil fuels are a major source of global energy and at the end of the 20^{th} they accounted for 85% of the total energy consumed [5]. Coal accounts for one third of the energy used in electric power generation. Gas turbines are being preferred for power generation because of their low level of CO_2 and NO_x emissions, small installation time and space and high cycle efficiency [6]. Gas turbines can operate on both liquid and gaseous fuels. The solid fuels such as coal, petroleum coke, biomass, municipal waste and other carbonaceous materials can also be gasified and cleaned then used in a gas turbine as synthetic gas(syngas).

The gas turbines are continuously being improved to increase their power output, efficiency, reduce their emissions, reduce fuel consumption, reduce their size and increase the life cycle. Gas turbine thermal efficiency has been increasing over the years. The increase is attributed to increase in turbine inlet temperature (TIT), which is currently $1200-1500^0$C and research is still being done to raise it higher. In the case of aircrafts, the power can be doubled by increasing the TIT from 1500 to 2000^0C [7]. The increase in TIT requires the turbine inlet blades to be made with a material that can withstand the extreme inlet temperatures, high pressure, high rotation speed, vibration and small circulation that are experienced at the first stage of a gas turbine [8]. More advanced turbine blade cooling techniques are being developed since the TIT for advanced gas turbines is higher than the melting point of blade material [9].

Blade cooling technologies are needed to ensure turbine operates safely since the current TIT is more than 500K higher than turbine blade materials melting points. Blade cooling was first used in gas turbine in Conway in 1962 and continue being improved [10]. Turbine blade design is being advanced to allow internal cooling channels and to withstand the thermal and rotational stresses. Research is still being

Agatha Mbeni Muinde, Department of Mechanical Engineering, JKUAT, phone: +254713103341; e-mail: amuinde@jkuat.ac.ke
Eng. Dr. Hiram Ndiritu, Department of Mechanical Engineering, JKUAT, e-mail:hndiritu@eng.jkuat.ac.ke
Dr. Benson Gathitu, JKUAT, phone: +254723118800 e-mail:bbg@eng.jkuat.ac.ke

done to determine the optimum shape and size of the blade holes for effective film cooling. Research is being done on effects of rotation on cooling and flow in the casing. Research needs to be done on the effect of velocity, temperature and turbulence profiles exiting the combustion chamber on film cooling of surface and end-walls of the first high pressure gas turbine blade.

Blade tip clearance - the space between the blade and the casing - is responsible for leakage mass flow across the blade tip from the pressure side to the suction side. The leakage causes reduced turbine efficiency by decreasing net work output of each rotor [11]. Further, the aerodynamic losses experienced in a stage are caused by tip leakage loss. Research is till ongoing on different ways to reduce it. This paper will be a review of the effects of blade tip loss and what is being done to reduce it.

II. REVIEW

A. Gas turbine

A gas turbines is used to convert the thermal energy into mechanical energy. Gas turbines are light, compact and have a high power to weight ratio [7]. Fig1 shows a schematic diagram of the actual gas turbine engine. It consists of compressor, combustor and turbine. The compressor is used to compress air from the atmosphere to the desired pressure, the combustor is used to burn fuel and the compressed air raising the gas temperature and the turbine converts the gas energy into power work and is coupled to the load which can be a generator for power generation or used to drive other systems.

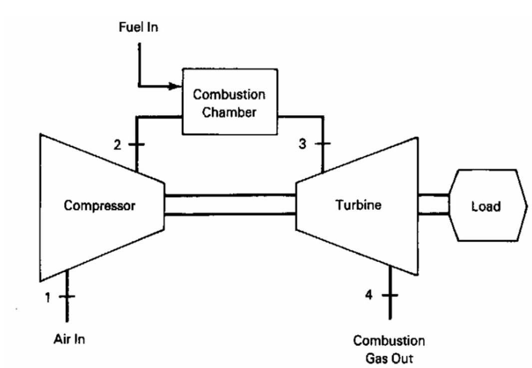

Fig. 1. Schematic diagram of a gas turbine engine

B. Turbine cooling

Blade cooling technologies are needed to ensure turbine operates safely since the current turbine entry temperature is more than 500^{o}C higher than turbine blade materials melting points [7]. Blade cooling was first used in gas turbine in Conway in 1962 and continue being improved [10]. Fig2 shows some of the blade cooling techniques used.

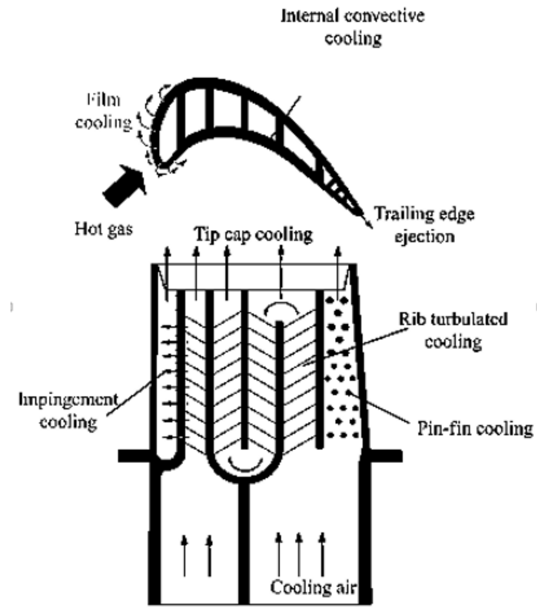

Fig. 2. Blade cooling techniques

Cooling techniques are being improved to cater for the increasing turbine inlet temperature. Trailing edge cooling is one of the techniques being explored. The blade needs to be thin so as not to cause aerodynamic losses. Horbach et al [12] did an experimental study on the performance of external film cooling of the pressure side cutback configuration. The experiment was done using different blade geometry and shapes. The highest cooling effectiveness was achieved in the thinnest ejection lip configuration though it is difficult to manufacture that design. The rounded shape of the tip caused increase in discharge coefficient and it also caused an increase in film cooling effectiveness at high blowing ratios which is a result of changed flow separation.

C. Film cooling

Film cooling is one of the blade cooling techniques. Cold air is injected from the inside of the blade to the outside surface forming a protective layer between the blade surface and the hot air surrounding the blades [13]. Film cooing effectiveness is affected by rotation speed, blowing ratio, pressure distribution and vortices around the leading-edge region of the gas turbine. The average film cooling effectiveness in the leading edge increases with blowing ratio. The film cooling effectiveness is higher at the suction while on the pressure side the film cooling effectiveness on the blade surface is lower due to presence of upstream wakes.

Film cooling effectiveness is affected by rotation and blade configuration [14]. The objective of the paper was to investigated the effect of tip ejection on film cooling effectiveness on a rotating turbine with four different tip blade configurations: plane tip with tip hole cooling, squealer tip with tip hole cooling, plane tip with pressure-side-edge compound angle hole cooling and squealer tip with pressure-side-edge compound angle hole cooling. An experimental was done using pressure sensitive paint technique. The film cooling efficiency is increased by increasing the Mach number of the flowing fluid across the different blades of shapes. The coolant particles from the cooling jet of the first two cooling holes of a plane tip blade move in the opposite direction of the blade rotation. Film effectiveness for plane tip increases with increase in rotation speed but decreases with increase in rotation speed for the other three blade shapes. In plane tip blade the film effectiveness follows net velocity vector of incident velocity and leakage velocity for different flow speeds. Research on the effects of heat transfer coefficients, cooling flow losses and stage losses on film cooling effectiveness for different blade configuration at different rotation speed needs to be done.

The direction of coolant flow affects the film cooling effectiveness [15]. A study on backward film cooling was done using numerical simulation and validated by tests. The backward injection has higher and more uniform cooling span then forward injection cooling. The film cooling effectiveness remains high at different blowing ratios in the case of backward injection cooling. The experiment done validated that backward injection is better than forward. A study on ways of improving film cooling effectiveness on curved surfaces need to be done.

Coolant density influences the film cooling effectiveness [16]. A study was done Pressure Sensitive Paint technique to determine film-cooling effectiveness at high blowing ratios, coolant density, and freestream turbulence intensity. The results showed that film cooling effectiveness increases with increase in blowing ratio on the pressure side from 1.2 to 1.7 and on the suction side from 1.1 to 1.4. Film cooling peak effectiveness on the pressure side is at momentum index of approximately 1.15 and at 0.75 on the suction side. Film cooling effectiveness increases proportionally to density ratio in the pressure side while a slight increase in effectiveness on the suction side is seen between axial chord points 0.2 and 0.45 and a major increase between axial chord points 0.45 and 0.75. Increase in freestream turbulence intensity decreases the film cooling effectiveness on the pressure side and on the suction side between axial chord 0 and 0.45 but it increases with increase in turbulence intensity after axial chord 0.45. A study needs to be done on ways of improving film cooling efficiency in turbulent.

D. *Steam-injection cooling*

Steam-injection cooling offers a potential increase in cycle efficiencies and work output at considerable cost for industrial gas turbines. Higher water flow rate is required to prevent boiling in the system, resulting in higher work output and lower cycle efficiency [17].

Steam injection affects performance parameters of gas turbine and nitrogen oxide emissions [18]. A study was done on gas turbine performance and NO_x production for two different ambient pressure with and without steam injection technique using modeling and analysis method. The results showed that steam injection cooling increased the thrust coefficient, thermal efficiency and turbine work output. The steam injected to the burner reduces NO_x production.

E. *Transpiration gas cooling*

It is used for cooling turbine blades when operating at very high temperature. An insulating film is created on outer airfoil surface by passing a cooling gas through a porous wire mesh skin. In cases where steam is used, the porous skin has to be selected such that the quantity of steam that penetrates meets the constant wall temperature at the local gas steam temperature and pressure conditions [19].

The performance of gas turbine when using steam or air as a coolant in transpiration is different [20]. Computer modeling was used to compare the performance of combined cycle with air and steam cooling. The results showed that the combined cycle efficiency and specific work output varied with TIT and coolant. As the TIT increased from 1600 K to 1800 K the difference in cycle efficiency between steam and air cooled turbine changed from 1.47% to 2%. The specific work output for a steam cooled combined cycle was 63kJ/kg higher than air cooled combined cycle at TIT of 1800 K. A study on the mixing losses caused by using Steam as a coolant needs to be done.

F. *Internal Cooling Method*

The turbine blades have internal channels where air extracted from the compressor is forced through hence cooling the turbine. Fig.3 shows a turbine blade with cooling channels. Internal cooling provides better cooling hence increasing the blade life. The main disadvantage is the many cooling channels that are complicated to machine [17].

Rotation affects the internal cooling of turbine blades. Han [13] did a study on blade cooling. The findings were that rotation can cause heating on one side of the cooling channel and cooling on the opposite side due to the secondary flow induced by the rotation. RANS method of turbulent flow is used in computing the flow and heat transfer. Rotation reduces the impingement cooling effect due to jet deflection away from the impinged surface.

G. *Tip leakage*

The clearance between blade tip and the casing causes turbine tip leakage loss. Reducing the turbine leakage loss in high pressure turbine can instantly save cost and increase the engine life [21].

The gas turbine rotation causes blade tip loses due to the vortices formed as the fluid passes between the blades and the casing. Liu et al [22] did a study on the effects of blade

Fig. 3. Turbine blade with cooling Channels

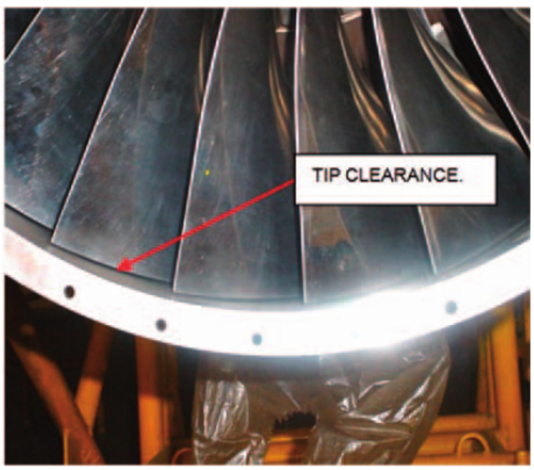

Fig. 4. Tip clearance

rotation on axial turbine tip leakage vortex breakdown and loss. Numerical techniques method was used. The finding were that the tip mixing loss per unit leakage flow reduced with increase in rotation speed. The vortex breakdown is influenced by Coriolis force and the 3D shear flow in the casing endwall region. Tip injection should be used to control vortex breakdown hence reducing tip leakage losses.

Yang [23] did a numerical simulation to study tip leakage flow and heat transfer in rotor blade with flat and squealer tips. A standard k-ω turbulence model was used to investigate the influence of tip gap height and groove depth on tip leakage flow and heat transfer. Leakage flow is reduced by increasing the tip groove depth up to 3% of the blade span above which any increase tip gap height causes increase in leakage flow. The average heat transfer rate decreases as the groove depth increases while it is increased on the tip surface with increase in tip gap height. When the tip gap height is less than 1% the overall heat transfer coefficient is affected by both vortex structure and leakage velocity but when the tip gap is more than 1% increase in heat transfer coefficient is proportional to increase in tip gap height which can only result from a variety of the leakage velocity.

H. Turbine Material

Material selection is very critical in the design of Gas turbines. Turbine blades operate at high stress conditions, at high temperatures and corrosion conditions. Temperature affects the performance of a gas turbine. As inlet temperature of gas turbine increases, specific fuel and air consumption decreases while the turbine efficiency increases. Nickel base super alloy especially Inconel 718 is used for turbine blade since it has excellent thermal stability, tensile and fatigue strengths, resistance to creep and hot corrosion and micro structural stability [24]. Blade cooling should be done to prevent hot corrosion and creep strain distribution on the trailing edge [25].

I. Turbine design

The gas turbines can be classified according to configuration as radial flow turbines; the flow is along the radius or as axial flow turbines; the flow is along the axis of rotation. The axial turbine can have of one or more stages, each consisting of a stationary nozzle and a rotor. The axial flow turbines are preferred to radial flow turbines because of the following reasons; they can be used for in compressible fluids, they have higher efficiency for high power range above 5MW and they have a high work factor hence a lower fuel consumption and less turbine noise [26]. The area of both the nozzle and the rotor decrease from inlet to the blade to the throat. The fluid enters at an angle tangent to the camber line at the leading edge and leaves at an angle tangent to the camber line at the trailing edge [27]. The first stage of a syngas turbine nozzle area is increased to a performance factor of 1.20 as compared to natural gas turbine nozzle that has a factor of 1.0 which results in a 20% flow area increase [28]. The efficiency of a gas turbine can be increased by increasing the blade area when using syngas in a natural gas turbine [29]. Research is still ongoing to establish an optimum blade area for syngas turbine.

The design specifications of a syngas turbine are; ambient conditions of 15^0C temperature, 1.013 bar pressure and relative humidity of 60%. Compressor with a pressure ratio of 16.2 and mass flow rate of 17.7 kg/s. Combustor fuel mass flow rate of 47% and pressure drop of 4%. The turbine has inlet temperature of 1314^0C, rotor inlet temperature of 1267^0C, exhaust flow rate of 550 kg/s and exhaust temperature of 587^0C [30]. The blades are 6 in number and the blade size is 100mm in length with tip outer diameter of 10mm and axial chord of 4mm. The flow parameters are; Inlet temperature of 1200^0C, rotation speed of 8400 RPM mass flow rate of 1 kg per second and discharge temperature of 850^0C. Fig.5 shows the axial flow turbine nozzle and rotor.

J. Syngas

It is produced through gasification of fuels such as coal, petroleum coke, biomass, municipal waste and other

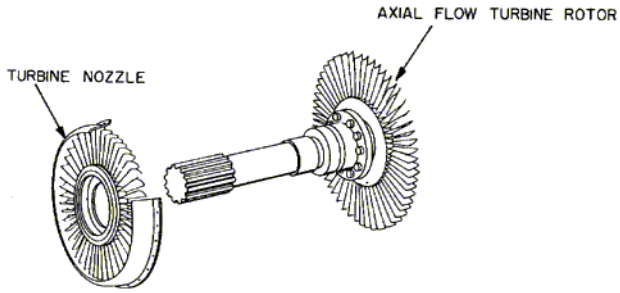

Fig. 5. Axial Flow Turbine Nozzle and Rotor

carbonaceous materials. It is a cleaner and high-value energy source and it is being used to replace natural gas in both power generation and industrial use [31]. Syngas from coal has a low heating value. Most of the existing gas turbines are manufactured specifically to burn standard fuels like natural gas and light diesel fuel. The main challenges facing gasification technologies are in efficient production and processing of quality syngas that is acceptable in gas turbine without reducing the life of turbine components. Since it is difficult to control the quality of the syngas in cases where the coal has high ash and moisture content [32].

A study on the influence of firing medium or low heat value fuel on the safe operation of a gas turbine was done by Xuelei [29]. The syngas flow rate was increased and the firing conditions changed. The compressor surge margin, axial torque and expander metal temperature were considered when changing operating conditions for the safe operation of the turbine. From the study the flow rate was increased by increasing compressor pressure ratio or by closing Inlet Guide Vane angle or by decreasing expander inlet temperature or by extracting air from compressor last stage or by increasing expander flowing area. Increasing the compressor pressure ratio increased the axial torque of the turbine, decreased the compressor surge margin and increased the expander temperature hence it was the worst safe performance strategy.

Oluyede [28] did a study on the fundamental impacts of firing syngas in a gas turbine while maintaining the hot section metal temperature. Syngas has a lower heating value as compared to natural gas, in order to attain the firing temperature and maintain constant energy input to the gas turbine a large fuel flow rate is required. The high hydrogen content in the syngas resulted in high flame temperature and high moisture content hence affecting the hot section of the material hence reducing the life of the turbine. The firing temperature was reduced by reducing the volume of syngas being burned.

K. Gaps

1) Research needs to be done on ways of improving film cooling efficiency in turbulent flow.
2) More research on the detailed and accurate leakage flow and heat and mass transfer characteristics over the blade tip and near-tip region and ways of reducing the leakage.
3) Research is needed on Ways of controlling the moisture content in syngas.
4) Research is still ongoing to establish an optimum blade area for syngas turbine.

III. Conclusion

There is a need to properly utilize the available sources of energy to meet the ever increasing energy demand. One of the cheap yet dirty source of energy is coal. Gasification of coal to produce syngas has aided in making coal a cheap and clean source of energy. Gas turbines are used to burn the syngas and convert it into ready energy like electricity. The gas turbine performance is still being improved by reducing the tip leakage loss and increasing the thermal efficiency. More research needs to be done to effectively reduce the turbine loss. Materials have been improved to cater for the high turbine inlet temperatures but cooling is still needed to achieve those high temperatures. More research is also needed to reduce the challenges faced when burning syngas in a gas turbine like high moisture content.

References

[1] U.S Energy Information Administration, *International Energy Outlook 2016 with Projections to 2040*, vol. 0484. 2016.
[2] Institute of Economic Affairs (IEA), "Situational Analysis of Energy Industry , Policy and Strategy for Kenya," p. 77, 2015.
[3] Energy Regulatory Commission, "POWER SECTOR MEDIUM TERM PLAN. Republic of Kenya," vol. 21, no. 21, 2014.
[4] Mobil Exxon, "The 2013 Outlook for Energy: A View to 2040," 2016.
[5] R. Bhargava, M. Bianchi, a. De Pascale, G. Negri di Montenegro, and a. Peretto, "Gas Turbine Based Power Cycles - A State-of-the-Art Review," *Power Eng. Conf.*, p. 11, 2007.
[6] M. Yuri, K. Tsukagoshi, S. Hada, J. Masada, and E. Ito, "Development of 1600 C-Class High-efficiency Gas Turbine for Power Generation Applying J-Type Technology," *Mitsubishi Heavy Ind. Tech. Rev.*, vol. 50, no. 3, pp. 1–10, 2013.
[7] B. Sunden and G. Xie, "Gas Turbine Blade Tip Heat Transfer and Cooling: A Literature Survey," *Heat Transf. Eng.*, vol. 31, no. 7, pp. 527–554, 2010.
[8] C. a. Estrada, "New Technology Used in Gas Turbine Blade Materials .," *Sci. Tech. Año XIII*, no. 36, pp. 297–301, 2007.
[9] D. Dongre, T. Vikas, and R. Vishal, "DESIGN AND ANALYSIS FOR INTERNAL COOLING OF GAS TURBINE BLADE," *Int. J. Eng. Appl. Technol.*
[10] L. Xu, S. Bo, Y. Hongde, and W. Lei, "Evolution of Rolls-royce Air-cooled Turbine Blades and Feature Analysis," *Procedia Eng.*, vol. 99, pp. 1482–1491, 2015.
[11] M. R. Shirzadi and H. Saeidi, "The Effects of Tip Clearance on Performance of a Heavy Duty Multi Stages Axial Turbine," *Proc. ASME Turbo Expo*, no. June 11-15, pp. 1–11, 2012.
[12] T. Horbach, A. Schulz, and H. Bauer, "TRAILING EDGE FILM COOLING OF GAS TURBINE AIRFOILS EXTERNAL COOLING PERFORMANCE OF VARIOUS INTERNAL PIN FIN CONFIGURATIONS," *Proc. ASME Turbo Expo 2010 Power Land, Sea Air Proc.*, no. mm, pp. 1–12, 2010.
[13] J.-c. Han, "Recent Studies in Turbine Blade Cooling ," *Int. J. Rotating Mach.*, vol. 10, no. 6, pp. 443–457, 2004.
[14] M. T. Schobeiri, M. Rezasoltani, K. Lu, and J. C. Han, "A Combined Experimental and Numerical Study of the Turbine Blade Tip Film Cooling Effectiveness under Rotation Condition," in *Turbine Tech. Conf. Expo.*, 2014.
[15] X. C. Li, G. Subbuswamy, and J. Zhou, "Performance of Gas Turbine Film Cooling with Backward Injection," *Energy Power Eng.*, vol. 2013, no. July, pp. 132–137, 2013.

[16] D. P. Narzary, K.-c. Liu, A. P. Rallabandi, and J.-c. Han, “INFLUENCE OF COOLANT DENSITY ON TURBINE BLADE FILM-COOLING USING PRESSURE SENSITIVE PAINT TECHNIQUE,” in *Power Land, Sea Air*, pp. 1–12, 2010.
[17] N. Nandakumar and N. S. Moorthi, “Performance Analysis of Gas Turbine Blade Cooling by CFD,” vol. 1, no. 4, pp. 3–9, 2015.
[18] R. Tirgar, A. M. Sarmazdeh, M. M. Nezhad, and M. Tahani, “Modelling of Steam Injection Effects on Performance Parameters and NOx Emissions of a Gas Turbine,” *J. Appl. Sci. Res.*, vol. 10, no. May, pp. 331–336, 2014.
[19] M. P. Boyce, *GasTurbine Engineering Handbook*. gulfProfrssional Publishing, 2 ed., 2002.
[20] S. Kumar and O. Singh, “Enhancement of combined cycle performance using transpiration cooling of gas turbine blades with steam,” *J. Mech. Sci. Technol.*, vol. 28, no. 6, pp. 2429–2437, 2014.
[21] L. Qi and Y. Zhou, “Turbine blade tip leakage flow control by unsteady periodic wakes of upstream blade row,” *Procedia Eng.*, vol. 80, pp. 202–205, 2014.
[22] J. Gao, Q. Zheng, Y. Liu, and P. Dong, “Effects of blade rotation on axial turbine tip leakage vortex breakdown and loss,” *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.*, vol. 0, no. 0, pp. 1–16, 2016.
[23] D. Yang and Z. Feng, “TIP LEAKAGE FLOW AND HEAT TRANSFER PREDICTIONS FOR TURBINE BLADES,” *Power Land, Sea Air*, no. May 14-17, pp. 1–8, 2007.
[24] R. J. E. Glenny, J. E. Northwood, and a. B. Smith, “Materials for Gas Turbines,” *Int. Mater. Rev.*, vol. 20, no. 1, pp. 1–28, 2013.
[25] T. V, U. P. S, P. G. Reddy, C. J. Manjunath, and A. Professor, “Design and Analysis of Gas Turbine Blade,” *Int. J. Innov. Res. Sci. Eng. Technol. (An ISO Certif. Organ.*, vol. 3297, no. 6, pp. 13533–13539, 2007.
[26] N. Binder, X. Carbonneau, and P. Chassaing, “Off-Design Considerations through the Properties of Some Pressure-Ratio Line of Radial Inflow Turbines,” *Int. J. RotatingMachinery*, vol. 2008, 2008.
[27] W. Bathie, *Fundamentals of Gas Turbines*. John Wiley & Sons, Inc., 2 ed., 1996.
[28] E. O. Oluyede and J. N. Phillips, “FUNDAMENTAL IMPACT OF FIRING SYNGAS IN GAS TURBINES,” *ASME Turbo Expo 2007 Power Land, Sea Air*, pp. 1–8, 2007.
[29] Z. Xuelei, W. Songling, C. Haiping, and Z. Lanxin, “The Influence of Firing Medium or Low Heat Value Fuel on the Safe Operation of Gas Turbine,” no. 93102802, pp. 1–3, 2010.
[30] D. W. Kang, C. M. Kim, J. H. Lee, T. S. Kim, and J. L. Sohn, “Performance maximization of IGCC plant considering operating limitations of a gas turbine and ambient temperature,” *J. Mech. Sci. Technol.*, vol. 30, no. 5, pp. 2397–2408, 2016.
[31] P. J. Roach and C. B. Ponton, “Aqueous electrophoretic deposition as a method for producing an investment casting shell mould ceramic face-coat. Part 1: Formation of a carbon-filled investment casting wax electrode material,” *J. Mater. Sci.*, vol. 48, no. 21, pp. 7476–7492, 2013.
[32] M. S. Bhatt, “Hybrid clean energy technologies for power generation from sub-bituminous coals: a case of 250 MW unit,” *Int. J. Sustain. Energy*, vol. 6451, no. March, pp. 1–14, 2012.